

Solvent Replacement for Green Processing

Julie Sherman,¹ Bain Chin,² Paul D.T. Huibers,¹ Ricard Garcia-Valls,¹ and T. Alan Hatton¹

¹Department of Chemical Engineering, ²Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts

The implementation of the Montreal Protocol, the Clean Air Act, and the Pollution Prevention Act of 1990 has resulted in increased awareness of organic solvent use in chemical processing. The advances made in the search to find "green" replacements for traditional solvents are reviewed, with reference to solvent alternatives for cleaning, coatings, and chemical reaction and separation processes. The development of solvent databases and computational methods that aid in the selection and/or design of feasible or optimal environmentally benign solvent alternatives for specific applications is also discussed. — *Environ Health Perspect* 106(Suppl 1):253–271 (1998). <http://ehpnet1.niehs.nih.gov/docs/1998/Suppl-1/253-271sherman/abstract.html>

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Introduction

Solvents, defined as substances able to dissolve or solvate other substances, are commonly used in manufacturing and laboratory processes and are often indispensable for many applications such as cleaning, fire fighting, pesticide delivery, coatings, synthetic chemistry, and separations (1). Billions of pounds of solvent waste are emitted to the environment annually, either as volatile emissions or with aqueous discharge streams (2). Many of these solvents are known to upset our ecosystems by depleting the ozone layer and participating in the reactions that form tropospheric smog. In addition, some solvents may cause cancer, are neurotoxins, or may cause sterility in those individuals frequently exposed to them. While contained use of these solvents would be acceptable from both an environmental and a health perspective, such operations are difficult to achieve, and alternative

solvents are currently being sought to minimize the problems inherent in solvent release to the environment.

As our awareness and understanding of how solvents affect the environment and human health grow, so do the regulations that govern use of these chemicals (Figure 1). Government agencies such as the Occupational Safety and Health Administration (OSHA) have been installed to protect workers from solvent exposure. Indeed, OSHA has implemented strict regulations, called permissible exposure limits (PEL), for chemical concentrations to which one may be exposed without detrimental health effects. Examples of the PEL values, as well as health effects for a variety of solvents, are listed in Table 1.

Other regulations aim at protecting the environment, which in turn has a positive impact on human and animal health. One

of the most stringent laws in this regard is the Montreal Protocol, which has banned the manufacture and use of stratospheric ozone-depleting solvents. Solvents restricted under this law are categorized as Class I or Class II compounds, many of which are listed in Table 2. Class I compounds have already undergone a major phase-out, whereas Class II compounds will be completely phased out of use by 2030.

Hazardous air pollutants such as hexane and methanol are regulated under the Clean Air Act (CAA) (3). Volatile organics, defined by the U.S. Environmental Protection Agency (U.S. EPA) as compounds that evaporate at the temperature of use and react with oxygen to form tropospheric ozone, are also restricted under the CAA. Further, the Toxic Release Inventory Bill requires solvent users to record their releases and waste carefully. A summary of many of the regulations at the federal, state, and local levels is found in a review by Breen and Dellarco (4).

The Pollution Prevention Act of 1990 propelled these regulatory issues to the forefront of process design by suggesting

... the use of materials processes or practices that reduce or eliminate the creation of pollutants or waste at the source. It includes practices that reduce the use of hazardous materials, energy, water or other resources and practices that protect natural resources through conservation or more efficient use. (5)

The U.S. EPA followed this Act by compiling a list of 17 priority pollutants, including some solvents and heavy metal compounds,

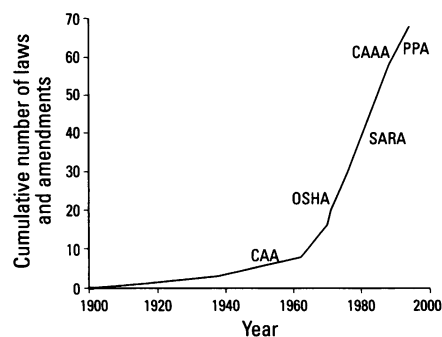


Figure 1. Cumulative federal regulations. Adapted from Gendron (200). Abbreviations: CAA, Clean Air Act; OSHA, Occupational Safety and Health Administration; SARA, Superfund Amendments and Reauthorization Act of 1986; CAAA, Clean Air Act Amendments; PPA, Pollution Prevention Act of 1990.

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
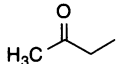
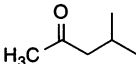

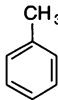

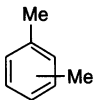
As part of this review, a Web site has been created that includes all links referred to in this paper. The Web site can be found at <http://web.mit.edu/huibers/www/greenchem.html>

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Address correspondence to Dr. T.A. Hatton, Department of Chemical Engineering, Massachusetts Institute of Technology, 25 Ames St., 66-309, Cambridge, MA 02139. Telephone: (617) 253-6600. Fax: (617) 253-8723. E-mail: tahatton@mit.edu

Abbreviations used: CAA, Clean Air Act; CAAA, Clean Air Act Amendments; CFC, chlorofluorocarbons; CFC-113, 1,1,2-trichloro-1,2,2-trifluoroethane; CMT, critical micelle temperature; HCFC, hydrochlorofluorocarbon; HFC, hydrofluorocarbon; MTBE, methyl *tert*-butyl ether; OSHA, Occupational Safety and Health Administration; PAH, polyaromatic hydrocarbon; P_c , critical pressure; PCBTF, parachlorobenzotrifluoride; PEG, polyethylene glycol; PERC, perchloroethylene; PEL, permissible exposure limits; PPA, Pollution Prevention Act of 1990; SAGE, Solvents Alternative Guide; SARA, Superfund Amendments and Reauthorization Act of 1986; SCCO₂, supercritical carbon dioxide; SCWO, supercritical water oxidation; SFE, supercritical fluid extraction; SHDS, Solvents Handbook Database System; SOLV-DB, Solvents Database; T_c , critical temperature; TCA, 1,1,1-trichloroethane; TCE, trichloroethylene; THF, tetrahydrofuran; U.S. EPA, U.S. Environmental Protection Agency; UV, ultraviolet; VMS, volatile methyl siloxane; VOC, volatile organic compound; WRRRC, Waste Reduction Resource Center.

Table 1. Compounds on the U.S. EPA 33/50 list.^a

Compound	Solvent use	Toxicity	OSHA PEL (8-hr TWA), ppm	LD ₅₀ , orally in rats
Benzene 	Synthesis, feedstock, waxes, oils, resins	Carcinogen	10	3.8 ml/kg
Chloroform CHCl ₃	Degreasers, rubbers, resins, waxes	Anticipated carcinogen	50	0.9 ml/kg
Carbon tetrachloride CCl ₄	Degreasers, rubbers, resins, waxes, feedstock	Poison, anticipated carcinogen	9528 ppm	
MEK (Methyl ethyl ketone) 	Coatings, resins	Headaches, dizziness, nausea	200	6.86 ml/kg
MIBK (Methyl isobutyl ketone) 	Similar to MEK	Similar to MEK	100	Similar to MEK
Methylene chloride dichloromethane CH ₂ Cl ₂	Polymers, synthesis, cleaning, and degreasing	Narcotic in high concentrations	25	1.6 ml/kg
PERC (Perchloroethylene) 	Dry cleaning, degreasing	Narcotic in high concentrations	100	8.85 g/kg
Toluene 	Feedstock, paints, resins, extractants, gasoline additive	Narcotic in high concentrations	200	7.53 g/kg
TCA (1,1,1-Trichloroethane methyl chloroform) H ₃ C-CCl ₃	Adhesives, coatings, inks, degreasers, waxes, alkaloids	Narcotic in high concentrations	350	0.58 ml/kg
TCE (Trichloroethylene) 	Cleaning, degreasers, waxes, resins, rubbers, paints, extractants, feedstock	Inebriation at moderate exposure. Heavy exposure can cause ventricular fibrillation, death	100	4.92 ml/kg
Xylenes 	General solvent, feedstock	Narcotic in high 100 concentrations	7.71 ml/kg	

^aToxicity information from Budavari et al. (107).

whose use was to be voluntarily reduced by 50% by 1995. This list, known as the U.S. EPA 33/50 list, was based on the criteria that the chemicals are used in large volume, they are detrimental either to the environment or human health, and there

are available methods to reduce their use (Table 1) (6). The 33/50 list in conjunction with the previously mentioned global and federal regulations has provided a solid starting point for scientists and engineers to reevaluate traditional methods

and to discover ways to limit or eliminate the use of hazardous solvents.

As a result, many methods for solvent pollution prevention have been developed (7,8). New synthetic pathways that do not demand the use of deleterious solvents or are

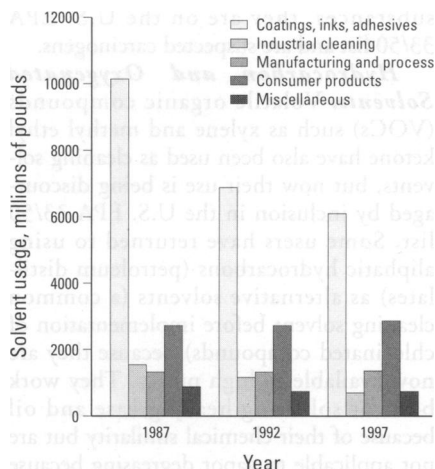
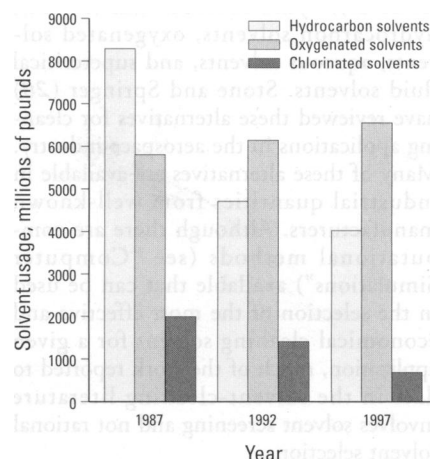
Table 2. Ozone-depleting solvents restricted under the Montreal protocol.

Class	Ozone-depleting substances
Class I	CFCs (chlorofluorocarbons)
	Halon 1211 (bromochlorodifluoromethane)
	Halon 1301 (bromotrifluoromethane)
	Halon 2402 (dibromotetrafluoroethane)
	CCl ₄ (carbon tetrachloride)
	Methyl chloroform (1,1,1-trichloroethane)
	CH ₃ Br (methyl bromide)
	C ₂ H ₂ BrF ₃ (hydrobromofluorocarbons)
Class II	HCFCs (hydrochlorofluorocarbons)

inherently more selective for the compound of interest have been investigated (9,10). Adjustments can be made to process equipment to protect against fugitive emissions (11). Process integration techniques have been effective in minimizing waste generation and optimizing solvent recovery and recycling (10,12–15). Solvent replacement techniques have also come to the forefront as many solvents are banned or discouraged from industrial use. In this case the only option is to find an alternative solvent.

The impact these regulations and methods have had on solvent use is seen clearly in Figures 2 and 3. Over the past 10 years the use of both hydrocarbon and chlorinated solvents has declined with only a minor increase in consumption of oxygenated solvents. In addition, while process solvents, consumer products, and various miscellaneous applications have exhibited fairly constant solvent consumption, the cleaning and coatings industries have markedly decreased solvent use over the last decade. A more detailed breakdown of U.S. solvent consumption can be found in an editorial by D'Amico (16).

The purpose of this review is to bring together research efforts in the quest to find "green" replacements for traditional solvents used in chemical processing. The first section discusses advances in solvent alternatives for cleaning, coatings, and synthetic processes such as reaction and extraction. The second section details advances in the development of solvent databases and computational methods that aid in the selection and/or design of feasible or optimal environmentally benign solvent alternatives for specific applications. Though important, halon substitutes for fire fighting do not fall into the category of chemical processing and will not be discussed here; readers are directed to a monograph by Mizolek and Tsang (17) for a comprehensive review of the challenges and progress in finding halon replacements.

**Figure 2.** Solvent use by application. Adapted from Kirschner (201).**Figure 3.** Solvent use sorted by solvent type. Adapted from Kirschner (201).**Table 3.** Main industrial sectors that use solvent cleaning.

Industrial sector	Type of cleaning	Type of soil cleaned
Electronic cleaning	Defluxing of printed circuit boards	Soldering rosin
Precision cleaning	Cleaning of sensitive parts such as optical devices and gyroscopes that have ultrahigh cleanliness standards	Organic residues, particulates
Metal cleaning	Surface preparation for machining or coatings	Oil, grease, particulates, inorganic salts
Dry cleaning	Cleaning of textiles that are not stable in aqueous solutions	Oil, organic residues

Green Alternatives for High Solvents Use Applications

Cleaning

Cleaning solvents are used in four main industrial sectors: electronics cleaning, precision cleaning, metal cleaning, and textile or dry cleaning, as indicated in Table 3. Within each of these industrial sectors, operations may be categorized as vapor degreasing, cold cleaning, or spot cleaning. Spot cleaning is a simple operation where an item is hand wiped with a solvent-soaked cloth to remove contaminants. Cold cleaning is usually performed by submerging the item to be cleaned in an ambient temperature solvent bath. As the item soaks, the contaminants dissolve in the solvent. These solvent baths have a limited lifetime because of contaminant accumulation. Vapor degreasing, on the other hand, is performed at high temperatures. The solvent is heated and the vapor contacts the article to be cleaned, condensing on it, and solvating the contaminants. The high temperature affords increased contaminant solubility. The solvent vapor remains contaminant free, but contaminants build up in the condensed

liquid. The choice of solvent and cleaning method depends heavily on the material of which the part to be cleaned is composed, chemical nature of the contaminant (often a grease or oil), geometry constraints of the item (i.e., small holes or bends and twists), and cleanliness criteria (18).

Historically, chlorinated solvents were preferred for cleaning applications because they are nonflammable, an important consideration if the cleaning process requires high temperatures such as in vapor degreasing. Of these, 1,1,1-trichloroethane (TCA) was the most widely used, but it has been found that 1,1,2-trichloro-1,2,2-trifluoroethane (CFC-113), trichloroethylene (TCE), perchloroethylene (PERC), and methylene chloride work well for such applications. However, under the Montreal Protocol and the CAA most of these solvents are restricted, forcing many processes to employ more environmentally friendly alternatives. Because there are so many considerations in choosing a cleaning solution, a universal "drop-in" replacement usually does not exist (16,19). As a result, a vast number of specialized alternatives are available in the form of hydrochlorofluorocarbons

(HCFCs), hydrofluorocarbons (HFCs), hydrocarbon solvents, oxygenated solvents, aqueous solvents, and supercritical fluid solvents. Stone and Springer (20) have reviewed these alternatives for cleaning applications in the aerospace industry. Many of these alternatives are available in industrial quantities from well-known manufacturers. Although there are computational methods (see "Computer Simulations") available that can be used in the selection of the most effective and economical cleaning solvent for a given application, much of the work reported to date in the solvent-cleaning literature involves solvent screening and not rational solvent selection.

Fluorocarbons. HCFCs and HFCs are alternative solvents that have been implemented in all industrial sectors except dry cleaning (21). These solvents exhibit many of the desirable solvent properties of chlorofluorocarbon (CFC) compounds such as high density, high dielectric strength, thermal stability, chemical stability, and non-flammability. Thus, they are as close as possible to a drop-in replacement for CFCs because their use requires minimal retrofitting. Because these compounds are not fully halogenated, they have lower ozone depletion potentials than CFCs (22). They have been shown to be as effective as CFC-113 in removing solder flux from electronic assemblies when used in an azeotropic mixture with methanol (23). These compounds have also been investigated in their "neat" form for the same purpose (24). Although they are effective cleaning solvents, HCFC and HFC compounds are considerably more expensive than CFC compounds, ranging from 2 to 5 times the cost because they require up to five synthetic steps to make versus one for many CFC compounds (25). Furthermore, HCFCs will be phased out by 2030, requiring those who use them to turn to other alternatives (26).

Perfluorocarbons are nonozone depleting but have long atmospheric lifetimes. They are suitable for some precision cleaning processes, as they effectively remove particles and aid in drying (27). Newly introduced fluoriodocarbons, which are nonflammable, noncorrosive, and appear to be nonozone depleting, are also emerging as possible replacements for CFCs (28). Some advocate using methylene chloride, PERC, and trichloroethylene as replacements for TCA and CFC compounds (29). Although methylene chloride and PERC are nonozone-depleting

substances, they are on the U.S. EPA 33/50 list and are suspected carcinogens.

Hydrocarbon and Oxygenated Solvents. Volatile organic compounds (VOCs) such as xylene and methyl ethyl ketone have also been used as cleaning solvents, but now their use is being discouraged by inclusion in the U.S. EPA 33/50 list. Some users have returned to using aliphatic hydrocarbons (petroleum distillates) as alternative solvents (a common cleaning solvent before implementation of chlorinated compounds) because they are now available in high purity. They work best for solvating heavy grease and oil because of their chemical similarity but are not applicable to vapor degreasing because of their flammability. In addition, although they are not ozone-depleting substances, many hydrocarbons are regulated as VOCs (22). Reynolds (30) recommends the Exxon line of high-purity hydrocarbon solvent as a replacement in chlorinated solvents for cleaning plastic substrates. In this case, the alternative solvent is able to solvate contaminants and the low surface tension results in desirable wettability.

For applications that require an oxygenated organic solvent to solvate contaminants such as grease, oil, wax, resins, and polymers, there are many available alternatives. A range of fluorinated organics is becoming available and these present attractive solvent substitutes. For example, pentafluoropropanol is a nonflammable, nonozone-depleting alcohol that can be used in situations in which alcohol is necessary for removing the contaminants (31). Similarly, hydrofluoroethers provide a safe alternative for processes in which ethers are needed (32). Dow Corning's line of volatile methyl siloxane (VMS) compounds may be used to remove simple oils, grease, and silicone elastomers in the same way as hydrocarbon solvents. VMS compounds have the advantage that they are neither hazardous air pollutants nor ozone depleters (32). *N*-Methyl pyrrolidone is a high-boiling solvent suggested for use in degreasing operations (33). It has an advantage over other solvents in that it is biodegradable, but because it is nonvolatile, a rinsing cycle is required to eliminate residue. VOC-exempt parachlorobenzotrifluoride (PCBTF) is another attractive solvent replacement option. PCBTF is being marketed for cleaning metal, plastics, electronic components, and glass while reducing volatile emissions (34).

Sometimes a two-step process is necessary to match the performance of chlorinated

solvents. Marino (35) suggests that using an ester-based proprietary solvent in combination with a perfluorohexane rinse in a retrofitted vapor degreaser to replace TCA is a cost-competitive option.

Aqueous Solvents. Another approach to solvent replacement is to switch from neat solvent to aqueous blends. These semi-aqueous solutions contain organic additives such as terpenes, alcohols, and aliphatic hydrocarbons. Terpenes are very effective in dilute aqueous solutions for removing grease, resin, and adhesives. They are naturally derived from plants and can be disposed of fairly easily (32). Although these compounds are not ozone depleters, caution must be used as the toxicity of terpene compounds has not been well characterized (36). Brown et al. (37) demonstrated that dilute aqueous terpene solutions could effectively replace TCA and methanol in cleaning metal parts for hip and knee replacements. Through a series of tensile tests, they demonstrated that the alternative cleaner worked up to 10% more effectively than the original solvents. In addition, they found that it was more economical to implement semi-aqueous cleaning than to use the conventional methods. Others have reported similar results but often note that use of semi-aqueous solutions requires some initial process modifications such as agitation and extra wash cycles (36,38-44). Another alternative solvent formulation uses aliphatic hydrocarbons diluted by water in the form of highly dispersed droplets stabilized by surfactants. These microemulsions, such as INVERT supplied by The Dow Chemical Company, (Midland, MI) have been found to be effective solvents for cold cleaning (19).

Aqueous solvents have also found a niche in replacing chlorinated cleaning solvents in applications such as printed circuit boards, turbine blades, advanced composites, and automotive motor housings (45). Table 4 compares the physical properties of assorted aqueous cleaning formulations with those of common chlorinated solvents. These solvents contain additives such as rust inhibitors, surfactants, or chelating agents and work best if they are slightly alkaline (46). They clean with similar effectiveness and have the advantage of being easier to recycle and reuse than conventional solvents. In an aqueous environment the "soil" will float to the top and may be skimmed off, as opposed to conventional solvents where the soil and solvent remain homogeneous and require energy for separation (47). Augias, Inc. has gone a step

Table 4. Comparison of aqueous and chlorinated cleaning solvents.^a

Physical property	CH ₂ Cl ₂	TCA	Aqueous A	Aqueous C
Boiling point, °C	39.8	74.1	100	100
Specific gravity	1.316	1.322	1.02	1.07
Flash point, °C	None	None	None	23.8
Vapor pressure, mmHg	340	90	—	—
Wt, lb/gal	10.98	10.92	<0.35	0.92
Surface tension, Dynes	28	28	29	33

Data from Quitmeyer (45).

Further by adding special nutrients to their aqueous replacement solvent, Oil Remover (32), which aid microbial growth so the contaminants are actually decomposed. As with the semi-aqueous solution mentioned above, aqueous replacement solvents often require process adjustments such as addition of agitation or ultrasonics (48). Further, the high latent heat of evaporation for water makes drying more difficult, and often extra equipment for proper and efficient drying is required (22).

Supercritical Carbon Dioxide. Above critical temperature (T_c) and pressure (P_c), fluids exist as one phase having densities and viscosities between those of a liquid and a gas and can have significantly different solvating capabilities than the liquid compounds below the critical point. Carbon dioxide (CO₂) is the most commonly used compound at supercritical conditions due to its accessible critical point ($T_c = 304.2\text{K}$, $P_c = 78\text{ atm}$). Supercritical CO₂ (SCCO₂) is a nonpolar solvent and thus is capable of effectively solvating nonpolar oils. Supercritical cleaning requires the parts to be placed in high-pressure chamber that is heated until the CO₂ is beyond its critical point. The supercritical solvent is swept over the parts to be cleaned and sent to a recovery unit. When the chamber is decompressed, any residual solvent evaporates because CO₂ is a gas at atmospheric pressure. This

method has been shown to work more efficiently for contaminated plastic than cleaning with CFC-113 (49). The primary application of SCCO₂ cleaning is in the cleaning of precision instruments where the highest cleanliness standards are required (50–56). SCCO₂ is also being investigated as a dry-cleaning solvent to replace PERC (57,58).

Solvent-Free Cleaning. Clearly, the most effective way to avoid problems with solvent contamination of the environment is to eliminate the use of the solvent entirely. Even though this clearly is not possible for most applications, there are some innovative solvent-free cleaning processes that deserve mention. Lu and Aoyagi (59) demonstrated that a pulsed KrF laser used to clean metal, magnetic material, plastic, and glass surfaces works very efficiently. It is a high-speed, area-selective, low-noise process. However, because of its area selectivity, it is suitable only for cleaning small areas, making it best for printed circuit board cleaning. Blasting with CO₂ snow or pellets is another way that coatings and contamination can be removed. Finally, steps can also be taken to eliminate the contaminant from ever entering the process. For example, the development of low solids “no clean” rosin fluxes for soldering printed circuit boards completely eliminates the need for a cleaning process (60).

Coatings

The function of a coating is to protect a surface from damaging environments such as extreme weather or corrosive chemicals. Coating technology spans a wide range of applications such as architectural, industrial, and antifouling coatings, and printing inks (61). Coatings are typically classified according to the binder or resin that acts as the film-forming agent and not according to the applications in which they are used. Table 5 lists typical binders and their primary applications. Additives (pigments, catalysts, antifoam agents, and hardeners) play a large role in determining the effectiveness and properties of the coating. The final component of a coating formulation is the solvent necessary to give the formulation a manageable viscosity for application. Table 5 also lists traditional formulation solvents used for each resin type. Many of the common formulation solvents such as xylene, toluene, MEK, MIBK, and methanol are classified as VOCs or appear on the U.S. EPA 33/50 list (62).

Not only are VOCs typically used in the coating industry, but they are used in large quantities, and the nature of the industry is such that solvent containment is much more difficult than in other areas of solvent usage. Consequently, solvent releases into the environment can be substantial. Figure 2 indicates that the coatings industry is the largest solvent consumer, using 7.5 billion pounds of solvent in 1992 alone. The large quantity of and long-term exposure to solvents that many painters face may cause chronic central nervous systems effects, cancer, and hematologic disorders (63). Fortunately, many advances have been made in coatings technology that allow the industry to substantially decrease the amount of solvent needed in the formulation of effective coatings—in some cases, to less than 3.5 lb VOCs/gal.

Table 5. Summary of resin types and applications.

Resin	Cure type	Formulation solvent	Application
Acetate	C	Hydrocarbons, toluene, xylene	Clear varnish, industrial enamels, printing inks, paint primer
Epoxy	C		Paint
Alkyd	C	Esters, diacetone	Heat-sensitive plastics, vehicles, home appliances, wood
Urethane	C		Paint, lacquer
Acrylic	C		Metal primer, marine enamels, tank and drum lining
Alkyd	C	Ketone, ethers, esters, toluene, xylene	Marine coatings, enamels, containers
Alkyd	C	Xylene, hydrocarbons, chlorinated hydrocarbons, ketones	Electrical insulating resins, paint additive, brick sealant
Alkyd	C/NC		Paint
Alkyd	NC	Ketones, esters	Wood finishing
Alkyd	NC	Ketones	Metal substrates
Alkyd	NC	Aromatic hydrocarbons, chlorinated hydrocarbons, esters, ketones	Alkaline substrates, marine coating
Alkyd	C		Automotive coatings, wood sealer and finish, concrete sealer

Abbreviations: C, convertible coating (reacts during cure); NC, nonconvertible coating.

High Solids Formulations. A coating is considered to be a high solids formulation when the binder and additive content is over 80% (w/w), although formulations having solids content between 60 and 80% are often included in this category (64). In high solids formulations, the approach is not to replace the conventional solvent with a less benign one such as is done in cleaning operations or to develop tailored solvents as is done in synthetic applications but merely to use less solvent. The advantages and disadvantages of high solids coatings are summarized in Table 6.

One of the main challenges in reducing the amount of solvent in a formulation is maintaining a manageable viscosity. Paint formulations with solids compositions up to 70% may still be thin enough to spray or roll, especially if application is done at a high temperature. Coatings that use natural oils such as linseed, tung, and soybean oil are often classified as high solids coatings and are prevalent in the history of coatings (65). In this case an oil is dispersed in a small amount of hydrocarbon solvent and as the solvent evaporates, the oil polymerizes on exposure to oxygen. However, purely oil-based paints such as these often discolor and are not durable; this has prompted the development of synthetic resins for high solids applications.

Many of the classes of resins listed in Table 5 may be used in high solids coating formulations. However, to attain coatings that contain less than 30% solvent, modifications must be made to the binders used in conventional formulations. This is accomplished by using lower-molecular-weight resins that undergo cross-linking reactions as the paint cures or by using resin polymers that have narrow molecular weight distributions. Some difficulties such as slow physical drying and film shrinkage are encountered when adjusting the polymer in this manner. However, these difficulties can be minimized by optimizing the formulation and cure conditions. For example, Bittner and Epple (66) demonstrated that polyurethane paint prepared in

a high solids formulation using resin of low molecular weight and narrow-size distribution dries with similar hardness and homogeneity if dried at 80°C rather than at ambient temperatures.

Modifying the molecular structure of the resin, e.g., by using branched resins (65), results in polymers with lower intrinsic viscosities. In turn, the coating formulation requires less solvent to reach a certain viscosity. In addition, it can be advantageous to pay close attention to the different monomer types used in a copolymer resin. For example, Sullivan (67) outlines using 2-methyl-1,3-propanediol to improve the flexibility of high solids polyester coatings, while reducing solvent usage. Another example of viscosity reduction is the use of silicon-based monomers in place of carbon-based monomers for the synthesis of polyester resins (68).

A related approach to high solids coatings is to incorporate a reactive chemical as the solvent. This allows control of the coating viscosity during application but minimizes the VOCs released because the solvent is cross-linked into the coating (69–74). Reactive diluents take many forms, sometimes even as a natural oil as in the case discussed by Dirlikov et al. (75) and Banov (76).

Of course, benign solvent use is encouraged in addition to quantity reduction. For example, VMSs similar to those described for cleaning have been used in three different high solids silicone paints, resulting in a VOC reduction without compromising film quality (77). Finally, the need for polymers with specifically tailored low molecular weights and distributions for effective high solids coatings has resulted in a variety of new polymerization initiators, synthetic techniques, and cross-linking additives (78–81).

Aqueous Formulations

Waterborne coatings offer another set of options as they provide a safe, nontoxic, and environmentally benign method to dramatically reduce or eliminate volatile

organic solvents. In addition, they are usually inexpensive and come in liquid form. Waterborne coatings, primarily in the form of latex paints, have been prevalent since the 1950s but were deficient in many areas such as flow behavior (because of their non-Newtonian nature), drying properties, glossiness, corrosion, and foaming (82). However, strict environmental regulations and concern for worker exposure have focused attention on these types of coatings and research is targeted at improving the durability and application of water-based coatings (83,84). Waterborne paints are applied by spraying, rolling, etc., but as with cleaning operations, the process usually requires some extra time and equipment to allow the coating to dry properly because of the high latent heat of water vaporization. The advantages and drawbacks of aqueous formulations are summarized in Table 7.

Waterborne paints fall into two general classes: water-reducible coatings and emulsions. Water-reducible coatings consist of binders that can be dissolved in water. The high polarity of water limits the range of resins compared to that for resins that can be used for high solids applications because of solubility difficulties. Resin classes that have been used successfully include epoxies, acrylics, polyesters, and polyurethanes. These resins differ from their solvent-borne counterparts used in high solids coatings through the addition of extra hydrophilic groups such as carboxylic acids and amines. General overviews of water-reducible polymers have been outlined (85,86).

If desired paint properties cannot be obtained using water-soluble resins, formulations using a surfactant to emulsify appropriate resins may be effective. These are often referred to as latex paints. The polymer is most commonly based on acrylate esters, vinyl acetate, or copolymers with styrene. The polymeric resin is prepared *in situ* in an emulsion polymerization resulting in a latex-type paint. The emulsions may contain up to 15% organic solvent as a stabilizer resulting in a low VOC coating. It is also worth mentioning that many water-reducible coatings contain small amounts of a co-solvent such as a glycol ether or alcohol to aid in coating handling (86).

Specific examples of tailored resins for waterborne coatings abound. Two-pack polyurethane paints have been developed that exhibit film properties comparable to those of solvent-borne polyurethane coatings (66,87). Waterborne polyurethanes that have the performance of solvent-based systems can also be made via tailored

Table 6. Advantages and disadvantages to high solids coating formulations.^a

Advantages	Disadvantages
Applicable to many resin types	Pigment flocculation
Equipment can be retrofit	Rheology difficult to control during application
Cost effective	May have inferior surface appearance
Excellent performance for protective maintenance and automotive coatings	

^aData from Varerkar (199).

Table 7. Advantages and drawbacks to waterborne coatings.

Advantages	Disadvantages
Inexpensive	High freezing point
Environmentally benign	High latent heat of vaporization
Nontoxic	Often need new equipment
Liquid form	Extra precautions with electrostatic paint application systems
	Limited material compatibility for delivery systems
	Can exhibit high water permeability
	Pigment flocculation

emulsion polymerization (88). Aromatic polycarbodiimides act as very efficient cross-linkers in waterborne emulsion systems and have the added advantage that they are much less toxic than traditional polyaziridines (89). Eslinger (90) discusses the use of aliphatic epoxy cross-linkers to cross-link acid functionalities that promote resin solubility. Cross-linking of the epoxy films results in a coating that is more resistant to humidity and mechanical impact. Waterborne fluoroelastomeric coatings for aggressive conditions have been developed (91). These coatings provide high-barrier properties and traditionally large amounts of solvent have been used to control viscosity during application. These new coatings are prepared in a latex form, are easily dispersed, and exhibit good resistance to heat and chemicals. The automotive industry, a large paint consumer, has recently implemented metallic water-based coatings (92). Finally, some waterborne coatings incorporate reactive diluents, as in high solids coatings. For example, Blank (93) describes using a urethane diol as a reactive diluent to replace glycol ether cosolvents in emulsion coatings.

Case studies illustrate that waterborne paints are indeed feasible for many applications. Waterborne paints can reduce the amount of solvent used in vehicle painting from 42.4 to 7.3 kg (94). Republic Container Co. (Nitro, WV), a company that supplies steel drums, switched from a solvent-based paint to a water-based paint, reducing their VOC emissions to 2.8 lb/gal and saving over \$10,000 in costs. Cornwell (96) illustrates many successful cases of waterborne paint use for steel coating, a substrate not traditionally coated with water-based paints because of difficulties with rusting.

Novel coating additives are also being studied as a way to ameliorate the disadvantages that have become synonymous with waterborne paints. Bieleman (82) discusses advances made in eliminating foaming, undesirable rheology, and poor glossiness due to agglomeration of the pigment.

Kobayashi (97) has also addressed the issue of pigment dispersion from the fundamental aspects of molecular interactions between water and the pigment. Klein (98) discusses latex paint formulations that are formulated without the glycols that are usually added as stabilizers but that may be toxic and contribute to the VOC content of paint.

Supercritical Carbon Dioxide Formulations. SCCO₂ is used in spray paint formulation and application because it is nontoxic, inexpensive, and has the added advantage that it has high solvation power for many polymers. Since CO₂ is so volatile, it is mixed with the coating resin immediately prior to application and the resulting mixture sprayed onto the substrate. It has been demonstrated that up to 80% of the organic solvent used to formulate an acrylic spray paint can be replaced by SCCO₂ without compromising the coating homogeneity (99). In addition, CO₂ is such a fast-evaporating solvent that the paint dries quickly. Furthermore, it does not generate additional CO₂ like solvent-containing paints that can oxidize to form 2.3 to 3 kg CO₂/kg solvent. White (100) reached conclusions similar to those of Donohue for a variety of resin-pigment combinations. Other researchers have patented their work with supercritical diluents for spray painting applications and demonstrated reductions in the amount of solvent required for adequate coating application (101,102).

Solvent-Free Formulations. As with cleaning, many researchers are looking toward solvent-free coatings as the answer to solvent replacement. Powder coatings rely on thermosetting plastics to be sprayed on a surface at high temperature. This method produces high-gloss, even coatings but requires specialized equipment and is limited to metal surfaces that can withstand the high-melt temperatures (65). Ultraviolet (UV) curable coatings are another solvent-free alternative. In this case reactive monomers such as ethers and

styrene are used to coat the surface of interest and UV light is used to initiate an *in situ* polymerization. Because the cure rate depends directly on the distance of the item to be coated from the UV source, this coating technique is best suited to flat sheets (103). A limitation is that it is difficult to incorporate pigment in UV cure coatings, as the pigments usually tend to absorb UV light. Finally, many novel coatings technologies are discussed in the review by McGinniss (104) who discusses advances made in environmentally benign coatings that include silicon oxides, silica fillers, and hybrid waterborne/UV-curable systems. Another researcher is exploring linear oligoester diols for solventless coatings (105).

Alternative Solvents for Synthesis

Solvents are used widely in the chemical processing industry as they are necessary for the solvation of the reactants and products in reaction processes. Selection of the solvent is important in determining the chemical reactivity, selectivity, and yield of industrial synthesis operations. Most synthesis solvents except carbon tetrachloride are not Class I or Class II ozone-depleting substances, so in contrast to solvents used in cleaning and coating operations, their supply is not threatened. Many of them, however, are on the 33/50 list, and ways to reduce their use are being sought actively. One route is to find or develop replacement solvents, which are attractive for reasons of safety, toxicity, emissions, and other aspects covered increasingly by the many government regulations. Ideally, new techniques would allow reactions to occur in the absence of solvents; to this end, some progress has been made using microwaves (106). Most synthetic reactions are solvent based, however, and will continue to be so for the foreseeable future. There is clearly a need, then, to search for alternative solvents for synthesis operations more environmentally friendly than the existing solvents. This search is more complicated than in the case of cleaning and coating operations as not only should the solvating characteristics of the replacements match those of the original solvent as closely as possible, but the new synthesis solvents must also be inert to the reactants and products, and the yield of the reaction should not be compromised.

Drop-in Replacements. As with other applications, the approach requiring the fewest modifications to already existing synthetic processes is to find a drop-in replacement for the conventional solvent.

For example, it is common to replace extremely flammable diethyl ether with methyl *tert*-butyl ether (107) or carcinogenic benzene with toluene (108). Such facile substitutions are not always available, however, and experimentation is often required to find a suitable replacement. Some examples of effective solvent substitutions are given in Table 8. In the synthesis of phosphonitrilic hydroquinone prepolymers, the carcinogenic and ozone-depleting solvent carbon tetrachloride was replaced with cyclohexane with a slight increase in yield (108). Chloroform was considered an explosive hazard in solvating Schmidt reactions involving azides, and it was replaced with dimethoxyethane (109). Dichloromethane, or methylene chloride, is one of the most popular synthesis solvents, but it is a suspected carcinogen and is highly volatile (bp = 40°C). Ogawa and Curran (110) demonstrated that benzonitrile (low toxicity, bp = 102°C) can be an effective replacement for dichloromethane in many reactions, with similar yields; some examples are shown in Figure 4.

Tetrahydrofuran (THF) is another important process solvent often used to solvate reactions involving strong bases. The workup of strong base reactions often includes an aqueous extraction, creating the problem of contaminated aqueous waste because THF is completely water-miscible. Typically, elaborate steps such as solvent exchange by distillation are taken to avoid THF contact with water. This is an energy-intensive process, and a more economical solution is desirable. Hatton's group (111) has examined the use of THF derivatives that have similar solvating characteristics but are essentially nonvolatile and water insoluble as reaction solvents. A particularly effective solvent is *n*-octyl tetrahydrofurfuryl ether, which has been shown to be a satisfactory replacement for THF in a series of reactions in the synthesis of the human immunodeficiency virus (HIV) protease inhibitor Crixivan. A number of solvent switches and off-line recovery operations can potentially be avoided using this approach. These solvents therefore satisfy the criteria for green processing

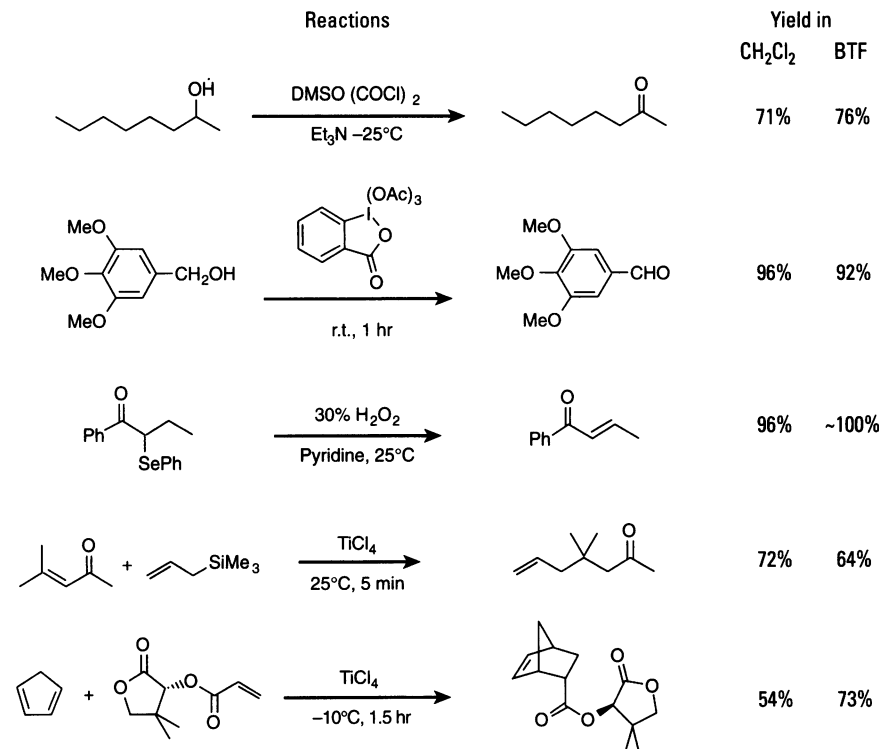


Figure 4. Benzonitrile as a replacement for dichloromethane.

in that they are less prone to enter the environment and that a number of energy-intensive separations and solvent exchanges can be avoided. Experiments have also shown that if THF is attached via an ether linkage onto a polystyrene-type polymer backbone, the solvent can be recovered efficiently through ultrafiltration (111).

Ionic Liquids. Seddon (112) showed that 1-ethyl-3-methyl imidazolium chloride-aluminum(III) chlorides are ionic liquids at temperatures as low as -90°C. These non-volatile ionic liquids can solvate a wide range of organic reactions including oligomerizations, polymerizations, alkylations, and acylations (113).

Water. Water is an ideal candidate as a replacement solvent. It is nontoxic, nonflammable, readily available, inexpensive, and easy to handle. Unfortunately, switching from organic to aqueous solvents is not a simple task. As with coating applications, the high polarity of water offers many difficulties

in its implementation as a reaction medium because many organic compounds do not exhibit good aqueous solubility. Nonetheless, significant progress has been made in developing reaction chemistries that take place in substantially aqueous environments. An overview of some of the advances in these areas is given here.

Phase transfer catalysis takes advantage of the solvating properties of biphasic systems. Reagents are solvated in the organic and aqueous phases and a phase transfer catalyst is used to bring them to react in the organic phase, as illustrated in Figure 5 (114). Aqueous alkali hydroxides can be used to replace flammable bases of sodium metal, sodium hydride, sodamide, and other alkoxides, whereas expensive anhydrous or aprotic organic solvents such as dimethylsulfoxide, dimethylformamide, and hexamethylphosphoramide can be replaced with dichloromethane, chloroform, hexane, and benzene. The reaction temperature is lowered while the reaction rate improves because the increased reactivity of anions in the nonpolar solvent. Reactions performed with phase transfer catalysts have been reviewed in several books (114–116), as have asymmetric phase transfer reactions (117).

Another approach is to perform the reaction at the organic–aqueous interface.

Table 8. Drop-in solvents for synthesis.

Solvent	Problem	Replacement	Reference
Diethyl ether	Flammable, flash point = -40°C	Methyl <i>tert</i> -butyl ether	(107)
Benzene	Carcinogenic	Toluene	(108)
Carbon tetrachloride	Carcinogenic, ozone depleting	Cyclohexane	(108)
Chloroform	Explosive hazard with azides	Dimethoxy ethane	(109)
Dichloromethane	Suspected carcinogen, volatile	Benzotrifluoride	(110)

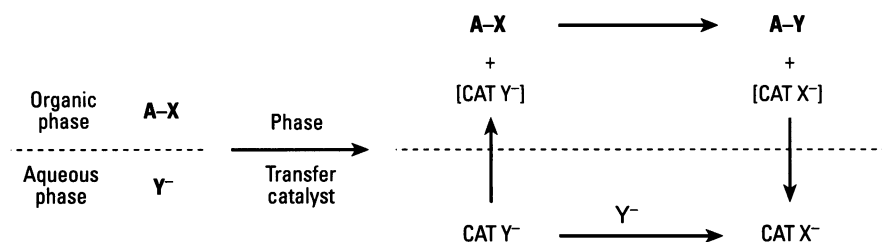


Figure 5. Phase transfer catalysis uses water to solvate some of the reagents.

Reagents are moved from the organic to the aqueous phase but remain localized near the interface, and thus the reagents need not be significantly water soluble. Catalysts are either solvated homogeneously in a supported thin aqueous film or at the interface by surface active ligands (118–120).

The use of the bulk organic solvent can be avoided completely by exploiting the properties of aqueous surfactant solutions in which the surfactants aggregate to form micelles consisting of apolar cores comprised of the hydrophobic tail groups stabilized by coronae formed by the hydrophilic surfactant heads (121,122). The apolar core plays the role of the organic solvent, whereas the palisade layer can provide a medium of intermediate polarity. The literature in this area is vast, but only a few of these studies specifically address the use of these aqueous micellar solutions as replacements for traditional organic solvents. For example, Monflier showed that solvent-free telomerization of butadiene with water to form octadienols could be carried out effectively in the presence of a nonionic surfactant; the conventional process is performed in the solvent sulfolane (123). Replacement of the organic phase with surfactants to exploit micellar phase transfer catalysis principles was reported recently by Rathman et al. (124) for the alkylation of phenol and aniline. This group had previously demonstrated the synthesis of a surfactant by micellar autocatalysis, whereby the surfactant product itself catalyzes the reaction (125).

In some cases even the use of micellar solvent phases can be avoided and the reactions can be carried out in an entirely aqueous medium. For water-soluble reagents, catalytic reactions such as hydrogenations and hydroformylations may be carried out homogeneously in the aqueous phase with water-soluble ligands such as triphenylphosphinitrisulfonate (120). Barbier-Grignard-type reactions in water (126) between allyl halides and carbonyl compounds can be mediated by metals of tin, zinc, or indium. Usually the generation

of the organometallic reagent takes place in anhydrous organic solvents, but using softer metals allows this reaction to take place in water. Shu et al. (127) demonstrated epoxidation of cyclooctene using oxone in water where the products were easily recovered by phase separation. The Shaw group has also shown that brominations are performed readily in water instead of in carbon tetrachloride (128). These examples indicate the potential minimization of solvent usage by the development of new water-based chemistries for green processing.

Supercritical Fluids. Water and carbon dioxide are the two most commonly used supercritical fluids for mediating reactions. These fluids are nontoxic, nonflammable, and inexpensive. However, the technology is expensive to implement, particularly for water because of the specialized equipment necessary to conduct reactions at high temperatures and pressures.

Supercritical water (647° K and 217 atm) is considerably less polar than water at ambient conditions and has the ability to solvate most organic molecules. In the presence of oxygen, organic compounds are quite reactive in supercritical water, with complete oxidation realized at short reaction times. Supercritical water oxidation (SCWO) processes are being developed for waste management as aqueous wastes containing 1 to 20% organics can be oxidized economically to CO₂ and water (129). For water with less than 1% organics, activated carbon is more economical for waste treatment and for water with greater than 20% organics, incineration is ideal. For in-depth discussions on SCWO, see Tester et al. (129) and Savage et al. (130). More recently, research has been conducted to improve catalysts (131) and reactors (132) that must withstand the corrosive conditions faced in SCWO operations.

SCCO₂, a nonpolar fluid, has been investigated as a solvent for many reactions in the areas of fuels processing, biomass conversion, biocatalysis, homogeneous and heterogeneous catalysis, environmental control, polymerization, materials synthesis,

and chemical synthesis), as reviewed by a number of authors (130,133,134). Most recently, Desimone's group has investigated this medium for precipitation polymerization of acrylic acid (135), synthesis of poly(2,6-dimethylphenylene oxide) (136), free radical telomerization of tetrafluoroethylene (137), cationic polymerization of vinyl and cyclic ethers (138), and dispersion polymerization of styrene (139). It has been found that fluorination and the formation of micelles with fluorinated surfactants enhance polymer solubility in SCCO₂ (139,140). SCCO₂ has been used as a solvent for homogeneous catalytic hydrogenations (141,142), and Burk et al. (143) have shown it to be a good medium for asymmetric hydrogenations.

Alternative Solvents for Separation Processes

The application of organic solvents and organic solutions with carrier compounds for the separation of organic substances and metal ions from different sources is well known. These separations are usually performed by extracting the target compound into the organic phase for purification, enrichment, and pollution remediation. As with cleaning, coating, and synthetic applications, it is advantageous to replace the organic solvents used in liquid extractions with solvents that are environmentally friendly. In some cases it is beneficial to implement new separation techniques that reduce the need for large volumes of organic solvents. Among these, liquid extraction techniques employing supercritical fluids and aqueous formulations containing surfactants or soluble polymers are most frequently considered because of their environmentally friendly characteristics and because they often afford increased extracting strength.

Supercritical Fluid Extraction. The characteristics of supercritical fluids make them ideal for the recovery of natural products (144). As a result, the food industry was among the first to implement supercritical fluid extraction (SFE) widely using CO₂. Not only is this process environmentally benign, it is also nontoxic, a primary concern when manufacturing edible products. Applications in the food industry include coffee decaffeination, and processes involving hops, vanilla, paprika, celery seed, and chili peppers (145). In one example, the extraction of grape seed oil using SFE yielded a final product of better quality than that obtained using conventional extraction (144).

SFE has also replaced many regulated solvents in analytical chemistry applications in recent years, primarily because it provides a more reliable measure of the concentrations of environmental contaminants and can play an important role in pollution assessment, abatement, and control. Dolezal et al. (146) have shown the advantages of using SFE compared to the conventional Soxhlet extraction with toluene for determining the presence of polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans in ashes from a municipal incinerator. SFE allows the complete extraction of the analytes from the sample, whereas conventional extraction results in an incomplete, and hence, inferior extraction. Analysis of agrochemical samples from soils after extraction by Soxhlet methods are now replaced by analysis following supercritical extractions (147). Alzaga et al. (148) extracted Pirimicarb (a pesticide present in sediments of rivers) using supercritical CO₂ modified with triethylamine and compared the results to those obtained with the conventional Soxhlet method. The supercritical fluid method offered increased precision, shorter analysis time, and a 10-fold reduction in solvent usage. Other efforts yielded similar results; for example, Reighard et al. (149) used CO₂ enhanced by the addition of methanol (co-solvent) to extract nitroaromatic and phenolics, environmental pollutants. This improved the procedure by reducing the solvent volume and the time necessary for the extraction. In addition, it allowed the extraction of polar species from complex pollutant matrices. The use of co-solvents can cause some technical problems, however, as high pressures and high temperatures may be necessary in these cases. In addition, some co-solvents may be regulated. An attractive interim option from an environmental standpoint is the use of HFCs or HCFCs. At supercritical conditions these solvents effectively extract relatively polar compounds such as polychlorinated biphenyls, dibenzo-*p*-dioxins, and dibenzofurans without the use of a co-solvent. (150).

Aqueous Surfactant and Macromolecular Solutions. Removal of organic or heavy metal ion contaminants from aqueous streams can be achieved using a variety of different separation strategies, one of which is solvent extraction. Potential countercontamination of the streams being treated with the extracting solvent can be avoided by eliminating the organic solvent altogether in favor of

aqueous-based solvent systems that rely for their effectiveness on the presence of dissolved surfactant micelles or polymers. These aggregates or polymers can solubilize organic solutes within the aqueous phase or form complexes with the metal ions to be removed. The question to be addressed is "how are the aqueous-based solvent systems to be separated from the treated feed stream?" Christian and Scamehorn (151) successfully investigated the use of ultrafiltration for the retention of the surfactant micelles, whereas Hurter and Hatton (152) argued that efficient separations could be obtained by exploiting the countercurrent principles entrenched in chemical engineering unit operations. They suggested that the micellar solutions be introduced to the lumens of a hollow fiber ultrafiltration unit and that the feed solution be introduced to the shell side of the unit at the opposite end of the module. The two streams then flow countercurrently, and the solute diffuses across the membrane from the shell side to the micellar solution, where it is taken up by the apolar micellar cores. The purpose of the membrane is to prevent the micelles from mixing with the aqueous feed stream.

A particularly important class of surfactants for the solubilization of organic compounds in aqueous solutions is the polyethylene oxide-polypropylene oxide-polyethylene oxide family of block copolymers (152,153). These polymers form polymeric micelles that have a high capacity for the solubilization of organic compounds. Recovery of polyaromatic hydrocarbons (PAHs) by using block copolymer micelles in hollow-fiber membrane extraction was successfully demonstrated by Hurter et al. (154). The high capacity of block copolymer micelles for trace contaminants offers the possibility of tailored design of block copolymers for future separations. An advantage of these polymeric micellar systems is that the micelles form only above a certain temperature, called the critical micelle temperature (CMT). When the loaded micellar solution is cooled below the CMT, the micelles dissolve and the PAH precipitates out of solution, thus enabling the simple and efficient regeneration of the micellar solution. These results and concepts have been confirmed by the more recent work of Lebens and Keurentjes (155).

Water-based solvent systems originally developed for the separation and purification of proteins and other biomaterials (156) have been suggested for the treatment

of contaminated aqueous waste streams. Certain pairs of water-soluble polymers are incompatible in solution together, and this can lead to phase separation in which two phases are formed. Both phases are predominantly water, and each contains only one of the two polymers. Similar phase behavior results with some polymers and high concentrations of organic salts. The properties of the two phases ensure that the environment-afforded targeted species is different in the two phases. This provides the driving force for separation of different species. A commonly used phase-forming polymer is polyethylene glycol (PEG), which may or may not be derivatized to impart added selectivity to the separation. Rogers' group has investigated the potential for using such systems for the separation and recovery of environmentally toxic heavy metals (157) and of pertechnetate from simulated Hanford tank wastes (158). The removal of color from textile wastes has also been addressed using such systems (158), which have the advantage that they are not organic-solvent based, are primarily water, and the PEG polymers used for phase separation are virtually non-toxic and nonflammable, are inexpensive and available in bulk, and have reasonable phase separation characteristics. As solvent replacements, then, PEG-based aqueous biphasic polymer systems are an environmentally favorable alternative to traditional organic solvent phases.

Another class of solvents that appears to have significant appeal for green processing of metal waste solutions relies on solvent-coated magnetic particles dispersed within the feed phase to be treated (159,160). Once the desired solutes have been removed by extraction, these particles can be recovered conveniently using magnetic filtration.

Computer Simulations

As computers become more pervasive and increasingly powerful, specialized programs and databases are being developed to assist in a wide variety of research efforts. This is true in the search for solvent alternatives, and in this section we review the application of computers to solvent substitution studies, and cover computer-aided molecular design of new solvents, methods developed for the prediction of physical properties, methods for predicting less precise chemical characteristics such as toxicity and carcinogenicity, and computer-aided design of alternative synthetic pathways. These tools may assist the scientist in two ways. First, the design process can be optimized with the use of

more complex constraints than could otherwise be handled. Second, in some cases the need for time-consuming and costly physical or chemical property measurements can be eliminated with the use of estimation techniques for properties of interest.

Computer-Aided Selection of Replacement Solvents

Several methods have been proposed to guide the solvent replacement process for the many applications described above. These efforts attempt to build an organized framework for this process and provide a substantial improvement over previously ad hoc or trial-and-error approaches to solvent replacement. An excellent example is the approach of Joback (161), who outlines a methodology for the selection of replacement solvents for various processes such as extraction or cleaning. There are basically four steps to this process: identify constraints on important solvent properties, compile data for all properties, rank solvents satisfying the target constraints, and evaluate top solvent candidates using simulation.

Constraints on the selection of a solvent are diverse. Environmental, safety, health, reactivity, stability, and regulatory considerations must be considered. To optimize solvent selection, these constraints must be quantified in terms of physical or chemical properties or molecular structure. Given that a number of properties can be determined to govern the constraints on the solvent application, accurate property values must be found in the literature, measured, or estimated. For compounds with unknown properties, measurement is often too costly to consider, so various property estimation techniques must be employed. For the third step, given the previously defined constraints imposed by the application, all candidate solvents are screened after which the remaining candidates can be put through a more rigorous trade-off analysis. If no solvents survive the screening, it must be determined which constraints can be eased until likely candidates appear. With available process simulation tools (Table 9), different solvent candidates can then be evaluated through the whole solvent life cycle. Additional costs and constraints, such as solvent storage, transportation, regulation and disposal costs, to name a few, must be considered outside those normally considered in a process simulation.

To perform a procedure such as that described by Joback (161), a significant amount of information must be obtained

on the solvents considered and their impact. There are many sources of solvent information available now on computer through the World Wide Web, several of which are summarized in the Appendix. Information on physical and chemical properties, government regulations covering the use of many solvents, and examples of successful solvent substitution efforts can now be readily accessed on the Web. The software used to evaluate candidates through simulation is generally a commercially available process simulator software package such as Aspen Plus, Pro II, and others (Table 9). These programs allow the simulation of engineering and operating problems, from the unit scale to full plant simulations. The impact on the entire plant of a proposed solvent substitution can be estimated using such a program.

Computer-Aided Molecular Design of New Solvents

Much current research on solvent substitution takes the process a step further than a simple screening of existing solvents by using an approach consisting of building new molecules from substituent molecular subgroups and using methods for predicting molecular properties from structure. This is done in the framework of a system in which the rules for the constraints to the solvent selection are defined and an optimization is performed. Several different approaches are used, with the most work published on algorithms using UNIFAC subgroups as a basis.

Development of the UNIFAC methodology by Fredenslund et al. (162) for the prediction of properties based on a group contribution approach stimulated much work in the area of computer-aided solvent design. The basis of the UNIFAC approach is the definition of submolecular groups (e.g., CH₂, CH₃, CH₃O, CH₂Cl, OH) and the fitting of a given molecular property or activity coefficient to a sum of contributions based on the subgroup molecular volume and interaction terms between the groups.

Separation processes (both liquid-liquid and gas-liquid) are a key element in many industrial processes. For this application, solvent molecules are built from UNIFAC submolecular groups, and the relevant properties of the new molecules such as distribution coefficients and selectivities are estimated. Strategies for the design of solvents for separation processes were initially formulated by Gani and Brignole and later extended to better model the processes of solvent synthesis, solvent evaluation, and solvent screening (163,164). Gani and Fredenslund (165,166) later expanded their computer-aided molecular design approach, and provided additional examples of the application of this approach to the selection of refrigerant alternatives, liquid-liquid extraction, azeotropic and extractive distillation, and gas absorption. Naser and Fournier (167) also employed UNIFAC group contributions, and developed a continuous optimization approach, as opposed to the combinatorial optimization approaches of

Table 9. Programs developed for property prediction, solvent replacement studies, and reaction design.

Program name	Application	Reference
	Organic synthesis	
CAMEO	Organic react.product pred.	www.chem.leeds.ac.uk/LUK
LHASA	Organic synthetic route design	www.chem.leeds.ac.uk/LUK
SYNGEN	Organic synthetic route design	syngen2.chem.brandeis.edu/syngen.html
	Process simulation	
LEMDS	Liquid-liquid extraction	Naser and Fournier (167)
Aspen Plus	Steady-state process simulation	www.aspentec.com
ChemCAD III	Steady-state process simulation	www.phoenix.net/~chemstat
HYSIM	Steady-state process simulation	www.hyprotech.com
PRO II	Steady-state process simulation	www.simsco.com
SPEEDUP	Dynamics and plant optimization	www.aspentec.com
	Property prediction	
UNIFAC	VLE prediction	www.cchem.berkeley.edu/~jmpgrp
ADAPT	General property prediction	zeus.chem.psu.edu
CODESSA	General property prediction	www.semichem.com/CODESSA.html
MOLCONN	Topological descriptor calculation	www.eslc.vabiotech.com/molconn
Henry, BIODEG, LogKow, etc.	Property prediction (several codes)	esc_server.syrres.com/~ESC/estsoft.htm Syracuse Research Corporation (nonprofit)
ACD/BP, etc.	Property prediction	www.acdlabs.com
DEREK	Toxicity prediction	www.chem.leeds.ac.uk/LUK
TOPKAT	Toxicity prediction	www.oxmol.com/prods/topkat/sw/

All links in this table, as well as those in the "Appendix" can be found in web.mit.edu/huibers/www/greenchem.html

others, to design optimum solvents for liquid-liquid extraction. Liquid-liquid extraction and multicomponent gas absorption solvent selection has been studied by Macchietto et al. (168) and solvent mixture selection by Odele and Macchietto (169). More recently, Pretel et al. (170) used a UNIFAC-based molecular design approach to evaluate solvents for liquid extraction and extractive distillation, and provide specific comparisons to experimental data.

Several researchers describe other aspects of the problem of designing new solvents. Klein et al. (170) investigated the design of solvent mixtures to achieve desired properties. Duvedi and Achenie (172) demonstrated a computer-aided molecular strategy to design environmentally safe refrigerants. Venkatasubramanian et al. (173) used a genetic algorithm to design molecules for given property constraints; this allowed a search over more diverse properties than possible with traditional algorithms. A design of an optimal polymer is given as an example. Meniai and Newsham (174,175) applied Monte Carlo simulations to develop relationships between the solute binding energy and both the solvent selectivity and the partition coefficient. This method is useful in designing liquid-liquid extraction processes.

Prediction of Physical Properties from Molecular Structure

At the core of many of these algorithms for solvent substitution is a method for predicting the properties of proposed molecules, given only the molecular structure. Much work has been done in this area alone, and several programs have been developed to guide this process. Some of these programs are listed in Table 9. Additionally, process simulation software such as Aspen Plus contain several different approaches for the prediction of properties from molecular structure.

Two different approaches for property prediction are apparent, one based on group contributions and one based on contributions influenced by more than just the immediate sum of group contributions, such as that captured by the topological descriptors (176). The first approach is the basis for programs such as the SRC and ACD programs, while the latter is used in MOLCONN, ADAPT, and CODESSA (Table 9) (177).

As an example, consider the prediction of aqueous solubility from molecular structure. The group contribution approach has been broadly applied, as reviewed by

Yalkowsky and Banerjee (178). More recently, efforts by Kan and Tomson (179) demonstrate the use of the UNIFAC approach to predict aqueous and nonaqueous solubilities for a variety of compounds. The topological approach is an extension of simpler group contribution efforts, as it can include contributions of higher order, where group contributions are essentially modified by contributions from nearest neighbors and beyond. Kier and Hall (180,181) developed a series of molecular descriptors termed the molecular connectivity indices and demonstrated their value in the prediction of many properties. Several other types of topological descriptors have been developed and applied to property prediction (176,182). Several research groups have taken the topological descriptors along with other types of molecular descriptors (geometrical, electrostatic, quantumchemical) and arrived at multiple linear regressions that allow the prediction of properties. With regard to aqueous solubility, several examples of this approach are the work of Nirmalakhandan and Speece (183), Bodor and Huang (184), and the Nelson and Jurs group (185,186).

Prediction of Toxicology and Related Parameters

Process simulation is a key tool in computer-assisted solvent substitution. Often the key to a successful simulation is selection of adequate models for the prediction of physical properties used in the simulation, as reviewed by Carlson (187). More complicated than the prediction of physical and chemical properties is the prediction of more loosely defined molecular characteristics such as toxicity. These properties are not traditionally included in process simulation software, so special attention must be paid to their prediction.

Traditionally, synthetic chemists focused on ease of synthesis and commercial use in chemical design. With ever increasing attention being paid to environmental impact and toxicity, additional constraints are being placed on the chemical design process. DeVito (188) outlines some of the approaches that chemists may consider for the design of safer substances; these include reducing absorption, understanding toxic mechanisms, using structure-property relationships, retrometabolism, isosterism, eliminating the need for associated toxic substances, and identifying equally useful but less toxic chemicals of another chemical class. The basis of chemical carcinogenesis is discussed by Lai et al. (189), who proposed

a molecular design method to reduce the carcinogenicity of compounds.

Prediction of chemical toxicity using a computer can save time and money (because of the high cost of toxicology studies) either by eliminating toxicological testing or by reducing the use of laboratory animals by improving the order of priorities for testing. Several approaches have been used to estimate toxicity of a given compound. Some approaches derive parameters from the molecular structure, and correlate those parameters with different common measures of toxicity. Others correlate toxicity with known physical properties of the compound of interest such as its octanol-water partition coefficient. Milne et al. (190) summarize various computer methods used to predict toxicity from molecular structure. It has been known for some time by medicinal chemists that toxicity, bioavailability, and other important parameters that gauge the interaction of chemical compounds with humans and animals correlate well with the octanol-water partition coefficient.

An attractive aspect of this approach is that an actual purified sample of the compound of interest is not necessary for property estimation, and no other measured properties are necessary, as the toxicity is correlated with molecular descriptors derived solely from molecular structure. Pioneering work in this area was done by Kier and Hall (180,181), who developed a series of topological descriptors called molecular-connectivity indices, and correlated toxicity and carcinogenicity with these indices. The fundamental concepts of the use of topological descriptors to predict chemical behavior has been summarized by Rouvray (176).

An example of another approach is DEREK (191,192), a publicly available expert system designed to assist chemists and toxicologists in predicting toxicological hazards based on analysis of chemical structure (Table 9). DEREK differs from other computer methods for toxicity prediction in that it makes qualitative rather than quantitative predictions and does not rely on algebraic or statistical relationships.

A variety of different approaches to the prediction of toxicity have been developed under the sponsorship of the Predictive-Toxicology Evaluation project of the National Institute of Environmental Health Sciences (193).

Computer-Aided Design of Alternative Synthetic Pathways

A more complicated problem than solvent replacement for applications such as cleaning

is that of solvent substitution for organic reaction optimization. The solvent is important in organic synthesis, and several solvent polarity scales have been developed to attempt to quantify this, specifically work by Reichardt (194).

Several programs have been developed to assist in this process. The CAMEO program (Table 9) uses a mechanistic approach to make predictions and does not rely on data tables of specific reactions. Consequently, it is capable of predicting novel chemistry. Given the reactant molecules and reaction conditions, CAMEO evaluates the reactions and suggests products. Another program, LHASA (Table 9), uses a chemical knowledge base that consists of an extensive library of reaction descriptors (transforms) based on reviews of the chemical literature. These transforms define the scope and limitations of each reaction type. The knowledge base is not just a restricted reaction database but enables LHASA to suggest new and innovative synthetic routes to chemists. Another program, SYNGEN (Table 9), automatically generates the shortest, most economic organic synthesis routes for a given target compound. Based on Hendrickson's half-reaction theory, it does not require a reaction database.

Several other approaches for automated design of synthetic pathways are discussed in the literature. Crabtree and El-Halwagi (195) develop the concept of environmentally acceptable reactions in which an optimization is done considering reactants and byproducts in an economic model toward the production of a certain product. Anastas (2) defines computer-assisted organic synthesis and describes software developed to identify alternative and potentially more benign reaction pathways for the synthesis of commercial chemicals. Optimization of both solvent design and reaction path design within the context of their previously defined methodology for environmental impact minimization is addressed by Stefanis et al. (196).

Modi et al. (197) have developed a software system, SMART (Solvent Measurement, Assessment and Revamping Tool) that allows assessment of solvents used for batch processing based on both empirical data and property estimation methods. This system includes a new conjugation-based method for the estimation of reaction rates in solution, which is based on the concept that the absolute reaction rate coefficient can be obtained from a function dependent on the change in molecular

charge distribution between reactants and activated complex (198).

Conclusions

Solvent replacement technology is a diverse field that affects many industries. It is a field driven by regulations implemented to protect our environment and health rather than for purely economic or scientific reasons. However, these regulations often translate to economic incentives and have given rise to many exciting and innovative technologies that otherwise might never have been developed.

In the cleaning and coatings industries, heavy government regulation has prompted the development of greener products, although the selection process for these new commercial products seems to be one of trial and error until a cost-effective solution is found. For synthetic applications, regulations are not as stringent, although it is recognized that significant processing advantages may be gained by using alternative solvents for existing processes or by developing new chemical routes to desired products that can exploit more benign solvent systems. Rational design and implementation of these solvents can lead to significant decreases in the environmental burden associated with solvent losses through vapor emissions and aqueous discharge streams and in energy usage through the simplification of process flow-sheets. Water-based systems are gaining attention, particularly in separations operations where in some instances aqueous surfactant and polymer solutions show considerable promise in emulating conventional organic solvents. These technologies, although many still in their infancy, seem promising as greener alternatives in their niche applications.

Finally, it is clear that many experimental efforts do not take advantage of the wealth of available computer databases and simulation techniques that may aid in selecting an appropriate replacement with minimal testing. The problem of finding suitable solvent substitutions has led to the development of several computer programs and databases to assist in the process. Of these computer-assisted techniques, several programs are publicly available, and for others, the algorithms have been described. The literature contains several examples of how these tools have been used to aid researchers in the selection of solvent alternatives for a number of applications. Specific tools have been developed to assist in the molecular design of solvent replacement molecules, to

predict physical properties from molecular structure, to predict activities such as toxicity and carcinogenicity, and to assist in the design of alternative synthetic pathways.

Appendix: List of Solvent Substitution Resources on the World Wide Web

Enviro\$en\$e

<http://es.epa.gov>

Sponsor: U.S. Environmental Protection Agency, Department of Defense Strategic Environmental Research and Development Program (DoD SERDP), Arlington, Virginia.

Enviro\$en\$e attempts to provide a single repository for pollution prevention, compliance assurance, and enforcement information databases. Included are pollution prevention case studies, technologies, points of contact, environmental statutes, executive orders, regulations, and compliance and enforcement policies and guidelines. A major component of Enviro\$en\$e is the database umbrella architecture for solvent alternatives. Enviro\$en\$e information may be used to implement pollution prevention and solvent substitution programs, ensure compliance with environmental laws and regulations, solve enforcement cases, and develop research projects. The search engine is capable of searching multiple web servers and offers assistance in preparing a search.

The Enviro\$en\$e project has a number of links to various solvent substitution data systems (<http://es.epa.gov/ssds/ssds.html>), including the Integrated Solvent Substitution Data System (ISSDS) (<http://es.epa.gov/issds>), which facilitates access to solvent alternative information from multiple data systems through a single, easy-to-use command structure, the "Solvent Alternatives Guide" (SAGE), the Hazardous Solvent Substitution Data System (<http://es.epa.gov/ssds/hssdstel.html>), an on-line, comprehensive system of product information, material safety data sheets, and other related information on alternatives to hazardous solvents and related subjects; the Joint Service Pollution Prevention (P2) Technical Library; the DoD Ozone Depleting Chemical (ODC)/Substance Information Exchange; and the Solvent Handbook Database System (SHDS) (<http://wastenot.inel.gov/shds>), a database providing access to environmental and safety information on solvents used in maintenance facilities and paint strippers. SHDS contains empirical data from laboratory testing. The Solvents Database

(SOLV-DB) (<http://solvdb.ncms.org>), will help a searcher find a wide variety of data on solvents quickly and easily. SOLV-DB will assist process engineers to make intelligent choices about which solvent to use for a particular application without incurring a legacy of problems. For hands-on users of solvents, a better understanding of solvent properties and of how to handle the material wisely can be gained using the SOLV-DB. SOLV-DB will also help environmental engineers delineate their responsibilities under routine conditions and in case of accidents. SOLV-DB can help members of the general public locate basic facts about materials of concern and help them appreciate the trade-offs involved in solvent selection. The Materials Compatibility Database provides laboratory test data to assist in implementation of ODC-free alternative solvents that are compatible with materials used in electronic assemblies.

Solvent Alternatives Guide

<http://clean.rti.org>

Sponsor: Research Triangle Institute, Research Triangle Park, North Carolina.

SAGE is a comprehensive guide designed to provide pollution prevention information on solvent and process alternatives for parts cleaning and degreasing. SAGE does not recommend any ozone-depleting chemicals. It is an interactive computer program designed to provide alternatives to solvent cleaning after obtaining information from the user about current cleaning processes and materials. Options are ranked numerically according to their potential for successfully fulfilling specific cleaning needs. Detailed descriptions of the cleaning technologies are provided by SAGE in addition to vendor information.

Coating Alternatives Guide

<http://cage.rti.org>

Sponsor: Research Triangle Institute, Research Triangle Park, North Carolina.

The Coating Alternatives Guide (CAGE) is a pollution prevention tool for small- and medium-size businesses and state technical assistance program representatives. CAGE is an expert system and information base designed to recommend low-emitting alternative coating technologies to coatings users. In addition, CAGE provides summarized information on recommended alternatives. The expert system asks the user several questions about their current coating process and tries to match alternatives that fit the user's operating conditions.

Joint Service Pollution Prevention Technical Library

<http://enviro.nfesc.navy.mil/p2library>

Sponsor: Naval Facilities Engineering Service Center, Port Hueneme, California.

The Joint Service P2 Technical Library comprises three main elements:

- The Joint Service P2 Opportunity Handbook was designed to identify available off-the-shelf pollution prevention technologies, management practices, and process changes that will reduce the amount of hazardous waste and solid waste being generated at joint service industrial facilities.
- The P2 Equipment Book is valuable for identifying commercially available P2 technologies already being purchased or evaluated by the Navy. The book includes equipment summaries containing detailed information on equipment characteristics, implementation requirements, benefits, associated costs, and contacts for further assistance.
- Defense Logistics Agency's "Environmental Products Catalog" is a user-friendly publication that clearly suggests alternatives to previously used products or processes. These alternatives may be nonozone depleting, less toxic, or promote recycling and waste minimization. The catalog also has an extensive contacts section to help customers request additional information.

Pacific Northwest Pollution Prevention Resource Center

<http://pprc.pnl.gov/pprc>

Sponsor: Pacific Northwest Pollution Prevention Resource Center, Seattle, Washington

The Pacific Northwest Pollution Prevention Resource Center works to protect public health, safety, and the environment by supporting projects that result in pollution prevention and toxics use elimination and reduction. The Center sponsors the "Pollution Prevention Technology Reviews" which covers alternative pollution prevention technologies that have been proven successful through actual research and demonstration projects (<http://pprc.pnl.gov/pprc/p2tech/p2tech.html>). The 1996 series of reviews focused on cleaning as a part of manufacturing. Additional reviews are planned in the future. The technology reviews offer links to projects listed in the Research Projects Database, links to other relevant Internet sites, and extensive bibliographies. The review series is intended for

manufacturers, researchers, and others interested in the details of new cleaning technologies. These reviews are divided into several sections to make it easier for users to locate information of interest. Each review includes an overview of the technology and its technical and economic performance, identification of research that has been done, and discussion of gaps in existing research. The topics covered are aqueous cleaning, supercritical carbon dioxide cleaning, "no-clean" technology, cleanliness measurement methods, cleaning-related projects in the Pollution Prevention Research Projects Database, and other cleaning-related Internet sites.

Waste Reduction Resource Center

<http://www.p2pays.org/wrrc>

Sponsor: Waste Reduction Resource Center, Raleigh, North Carolina.

The Waste Reduction Resource Center (WRRC's) clearinghouse staff provides access to and supports the collection of waste reduction information. The clearinghouse collection contains more than 8000 journal articles, case studies, technical reports, books, and video tapes. You may read or download the bibliography. The topics cover all general industry categories, manufacturing processes, hazardous waste streams, and water and air discharges. Specific information includes economical and technical data, process descriptions, waste reduction techniques, and implementation strategies. The collection also contains information on municipal recycling, solid waste reduction, environmental audits, and perspectives in pollution prevention. In addition, the WRRC has listings of numerous electronic bulletin boards providing information on environmental issues and technologies. An example is the online guide Solvents—The Alternatives that summarizes existing cleaning technologies, equipment, and cleaning procedures. Included are tables representing a cross section of products available and where additional information can be obtained.

Environmental Software Resource Guide

<http://www.envirosw.com/software.html>

Sponsor: Environmental Software Cooperative, Ventura, California

The "Environmental Software Resource Guide" is a database application containing information on approximately 2200 software products for the environmental management field and over 600 environmental

software vendors. This resource is currently being used by a wide range of public agencies, private companies, and environmental consultants around the globe. The database is drawn from a variety of sources; product availability and other information is verified annually through direct vendor surveys.

A Brief Survey of Pollution Prevention Software

<http://www.seattle.battelle.org/services/e%26s/Folder/P2/survey.htm>

Sponsor: Battelle Seattle Research Centers. Report prepared for Idaho National Engineering Laboratory, Idaho Falls, Idaho, September 1993.

A number of available software packages are useful for implementing pollution prevention in manufacturing processes. These packages apply to different organizational levels of decision making (policy, management, or operations) and reflect different degrees of pollution prevention orientation. For example, although some packages are explicitly designed for pollution prevention, others do not explicitly include pollution prevention components but could still be useful if applied to pollution prevention. The purpose of the survey is to identify gaps in the available packages that represent opportunities for software development and to identify particular software packages that represent opportunities for value-added extension or enhancement. To this end, this survey has located software packages that represent opportunities for development or

that illustrate the current state of the market. It describes these packages in terms of the following two characteristics: the explicit inclusion of pollution prevention functions; and the ability to support structured learning, so users can learn about their production processes and how to incorporate pollution prevention measures into those processes.

This survey identified 31 software packages that merited consideration. Of these, 20 were identified as having at least one of the above characteristics. Eleven other packages are also included in the final list because they represent potential opportunities for further development efforts or because they are representative of the software found.

Clean Process Advisory System

<http://cpas.mtu.edu>

Sponsor: This system was codeveloped by the National Center For Clean Industrial And Treatment Technologies, Houghton, Michigan, the AIChE/Center for Waste Reduction Technologies, New York, New York and the National Center for Manufacturing Sciences Ann Arbor, Michigan.

The Clean Process Advisory System is a system of software for efficiently delivering information on clean technologies and pollution prevention methodologies to the conceptual process and product designer on an as-needed basis. The system is meant

to address the challenge of incorporating environmental considerations into conceptual process and product design where most of the waste can be reduced in a cost-effective manner.

Environmental Professional's Homepage

<http://www.clay.net>

Sponsor: GZA GeoEnvironmental Technologies, Inc. Newton, Massachusetts.

This site is designed specifically for environmental consultants and remediation professionals. It contains links to the following information: federal government agencies; state government agencies; federal regulations references; health and safety issues; professional associations; conference bulletins, announcements; The EP Virtual Desktop; federal legislation; search engines; and EPA-Environmental Response Training Program training courses.

RiskWorld

<http://www.riskworld.com>

Sponsor: Tec-Com, Inc., Knoxville, Tennessee.

RiskWorld is an international World Wide Web publication covering news and views on risk assessment and risk management. It contains risk-focused news articles, government reports, paper abstracts, Web-site profiles, and more. This site also contains Internet links to sources of software for risk analysis, toxicology, and site remediation.

REFERENCES

- Grayson M, ed. Industrial Solvents. New York: Wiley and Sons, 1983.
- Anastas PT. Benign by design chemistry. In: Benign by Design: Alternative Synthetic Design for Pollution Prevention, ACS Symposium Series 577 (Anastas PT, Farris CA, eds). Washington: American Chemical Society, 1994;1-21.
- U.S. EPA. Clean Air Act-Code of Federal Regulations, Title 40, Part 60. Washington: U.S. Environmental Protection Agency, 1990.
- Breen JJ, Dellarco MJ. Pollution prevention: the new environmental ethic. In: Pollution Prevention in Industrial Processes (Breen JJ, Dellarco MJ, eds). Washington: American Chemical Society, 1992;2-32.
- U.S. EPA. EPA Pollution Prevention Directory. Washington: U.S. Environmental Protection Agency, 1990.
- U.S. EPA. 33/50 Program EPA-741-K-92-001. Washington: U.S. Environmental Protection Agency, 1992.
- Englehardt JD. Pollution prevention technologies: a review and classification. J Hazard Mater 35:119-150 (1993).
- Venkataramani ES, Vaiyda F, Olsen W, Wittmer S. Create drugs, not waste. CHEMTECH 674-679 (1992).
- Haggin J. Innovations in catalysis create environmentally friendly THF processes. Chem Eng News 73:20-23 (1995).
- Sheldon RA. Consider the environmental quotient. CHEMTECH 38-47 (1994).
- Lipton S. Reduce fugitive emissions through improving process equipment. Chem Eng Prog 88:61-67 (1992).
- Ahmad B. Synthesis of Batch Processes with Integrated Solvent Recovery [Ph.D dissertation]. Cambridge, MA: Massachusetts Institute of Technology, 1997.
- Dienemann EA, Bacher S. Pollution prevention case studies. In: Environmental Strategies Handbook (Kolluru RV, ed). New York: McGraw Hill, 1994.
- Manousiouthakis V, Allen D. Process synthesis for waste minimization. AIChE Symposium Series 91:72-86 (1995).
- El-Halwagi MM. Synthesis of reverse-osmosis networks for waste reduction. AIChE J 38:1185-1198 (1992).
- D'Amico E. Alternatives finding way in a stormy market. Chem Week 157:54-55 (1995).
- Miziolek AW, Tsang W, eds. Halon Replacements: Technology and Science. Washington: American Chemical Society, 1995.
- Million JF, McIlroy K, Zawierucha R. A selection and evaluation protocol for alternatives to halogenated hydrocarbon solvents for oxygen-cleaning purposes. In: Alternatives to Chlorofluorocarbon Fluids in the Cleaning of Oxygen and

- Aerospace Systems and Components, Vol 1181 (Bryan CJ, Thompson G, eds). Philadelphia:American Society for Testing and Materials, 1993;141-152.
19. Hairston D. Industrial solvents step up to the mound. *Chem Eng* 102:57-60 (1995).
20. Stone KR Jr, Springer J Jr. Review of solvent cleaning in aerospace operations and pollution prevention alternatives. *Environ Prog* 14:261-265 (1995).
21. Basu RS, Zyhowski GJ. Environmentally safer hydrochlorofluorocarbon solvents as CFC alternatives for cleaning. *Proc Inst Environ Sci* 37:247-251 (1991).
22. Koelsch JR. Breathe easy. *Manuf Eng* 111:49-54 (1993).
23. Bonner JK. New solvent alternatives to CFC cleaning. *Int Society for the Advancement of Material and Process Engineering Electron Conf* 3:797-803 (1989).
24. Hey D. Cleaning chemicals for electronics. Alternatives to ozone-depleting solvents. *Spec Chem* 10:449-450 (1990).
25. Manzer LE. Chemistry and catalysis. In: *Designing Safer Chemicals: Green Chemistry for Pollution Prevention*, Vol 640 (DeVito SC, Garrett RL, eds). Washington:American Chemical Society, 1996;144-154.
26. Anderson SO. 1994 Report of the Solvents Coatings and Adhesives Technical Options Committee for the 1195 Assessment of the UNEP Montreal Protocol on Substances that Deplete the Ozone Layer. Nairobi:United Nations Environment Program Solvents, Coatings, and Adhesives Technical Options Committee, 1995.
27. Kanegsberg B. Precision cleaning without ozone-depleting chemicals. *Chem Ind (London)* 20:787-791 (1996).
28. Higgins T, Thorn J. Solvents: know your options. *Chem Eng* 101:92-100 (1994).
29. Rupp VL, Hickman JC. Replacing 1,1,1-trichloroethane with other chlorinated solvents. *Plat Surf Finish* 82:34-38 (1995).
30. Reynolds JM. Cost effective replacements for chlorinated solvents and glycol ethers. *Spray Technol Market* 1:32-36 (1991).
31. Lea C. Solvent alternatives for the 1990's. *Electron Commun Eng J* 3:53-62 (1991).
32. Hairston DH. Degreasers: lift up and split out. *Chem Eng* 103:69-72 (1996).
33. McGill KM. Pollution prevention in army maintenance. *Int SAMPE Symp* 39:692-702 (1994).
34. Oxsol 100. Dallas:Oxychem, 1992.
35. Marino FA. A New process alternative for replacing ozone-depleting solvent cleaners. *Plat Surf Finish* 80:41-45 (1993).
36. Wolf K. The truths and myths about water-based cleaning: a systems approach to choosing the best alternatives. *Pollut Prev Rev* 4:141-153 (1994).
37. Brown LM, Springer J, Bower M. Chemical substitution for 1,1,1-trichloroethane and methanol in industrial cleaning operation. *J Hazard Mater* 29:179-188 (1992).
38. Kennedy ML. Getting to the bottom line: how TCA shows the real cost of solvent substitution. *Pollut Prev Rev* 4:155-164 (1994).
39. Goeders DC, Bridge DW, Boyaner MR. Investigation of the cleaning effectiveness of the alternative solvents and solvent cleaning. *Int SAMPE Symp* 39:1156-1170 (1994).
40. Copeland AE. Biodegradable solvent substitution. In: *Solvent Substitution, Annual International Workshop*. 4-7 December 1990, Phoenix, Arizona. Washington:Department of Energy, 1990;115-117.
41. Snyder JT. Aqueous degreasing: a viable alternative to vapor degreasing. In: *Solvent Substitution, Annual International Workshop*. 4-7 December 1990, Phoenix, Arizona. Washington:Department of Energy, 1990;177-179.
42. Thompson LM, Sinamdlie RF, Richards HL. Chlorinated solvent substitution program at the Oak Ridge Y-12 plant. In: *Solvent Substitution, Annual International Workshop* 4-7 December 1990, Phoenix, Arizona. Washington:Department of Energy, 1990;135-142.
43. Karrs S, McMonagle M. An examination of the payback for an aqueous cleaner recovery unit. *Plat Surf Finish* 80:45-50 (1993).
44. Hayes M. Semi-aqueous cleaning: an alternative to halogenated solvents. *Proc Electron Compon Technol Conf* 40:247-252 (1990).
45. Quitmeyer J. Aqueous cleaners challenge chlorinated solvents. *Pollut Eng* 23:88-92 (1991).
46. Quitmeyer J. The evolution of aqueous cleaner technology. *Met Finish* 93:34-49 (1995).
47. Nicholls LC. Creating a better environment. *Finishing* 14:51-52 (1990).
48. Lowell CR, Sterritt JR. Improving aqueous cleaning power. *Surf Mount Technol* 4:26-28 (1990).
49. Salerno RF. High pressure supercritical carbon dioxide efficiency in removing hydrocarbon machine coolants from metal coupons and component parts. In: *Solvent Substitution, Annual International Workshop*. 4-7 December 1990, Phoenix, Arizona. Washington:Department of Energy, 1990;79-86.
50. Weber DC. Precision surface cleaning with supercritical carbon dioxide. *Met Finish* 93:22-23 (1995).
51. McGovern WE, Moses JM, Weber DC. The use of supercritical carbon dioxide as an alternative for chlorofluorocarbon (CFC) solvents in precision parts cleaning applications. *Proceedings Air Pollution Control Association Annual Meeting* 11:94-RP137.03 (1994).
52. Supercritical fluids for cleaning metal parts. *Hazard Waste Consult* 13:1-25 (1995).
53. Hjeresen D, Silva L, Spall D, Stephenson R. National Program for Supercritical Fluids Cleaning. *Int SAMPE Symp Exhibit* 39:1109-1115 (1994).
54. Mchardy J, Stanford TB, Benjamin LR, Whiting TE, Chao SC. Progress in supercritical CO₂ cleaning. *SAMPE J* 29:20-27 (1993).
55. Gallagher PM, Krukoni VJ. Precision parts cleaning with supercritical carbon dioxide. In: *Solvent Substitution, Annual International Workshop*. 4-7 December 1990, Phoenix, Arizona. Washington:Department of Energy, 1990;70.
56. Purtell R, Rothman L, Eldridge B, Chess C. Precision parts cleaning using supercritical fluids. *J Vac Sci Technol* 11:1696-1701 (1993).
57. Prototype CO₂ dry-cleaning process replaces toxic solvent. *Environ Sci Technol* 29:497A(1995).
58. Iliff RJ, Mitchell JD, Carty DT, Latham JR, Kong SB. Liquid/Supercritical Carbon Dioxide/Dry Cleaning System. Oakland, CA:The Clorox Company, 1995.
59. Lu Y, Aoyagi Y. Laser-induced dry cleaning in air: a new surface cleaning technology in lieu of CFC solvents. *Jpn J Appl Phys* 33:L430-L433 (1994).
60. Sapre A. Electronic assembly solvent substitutes. In: *Solvent Substitution, Annual International Workshop*. 4-7 December 1990, Phoenix, AZ. Washington:Department of Energy 1990;131.
61. Oil and Colour Chemists' Association, Australia. *Surface Coatings: Paints and Application*, Vol 2. New York:Chapman and Hall, 1984.
62. Morgan RE. Put the lid on VOC emissions from maintenance coatings. *Chem Eng Prog* 92:54-59 (1996).
63. Burgess WA. Recognition of Health Hazards in Industry: A Review of Materials and Processes, Vol 538. New York:John Wiley and Sons, 1995.
64. Holmberg K. High Solids Alkyd Resins. New York:Marcel Dekker, 1987.
65. Elvers B, Hawkins S, Schuly G, eds. *Ullmann's Encyclopedia of Industrial Chemistry*. New York:VCH Publishers, 1985.
66. Bittner A, Eppe U. Aqueous and high solids two-pack industrial finishes complying with the regulations governing the emission of volatile organic compounds. *Surf Coat Int* 4:177-183 (1996).
67. Sullivan CJ. High solids performance polyesters with MPD: performance by design. *Am Paint Coat J* H79:80-89 (1994).
68. Thames SF, Panjnani KG. Organosilanes in low volatile organic component coatings. *Prog Org Coat* 26:63-71 (1995).
69. Johnson TL. Ultra-low viscosity oxazolidine and aldimaine-based reactive diluents for high-solids polyurethane coatings. *J Coat Technol* 67:41-47 (1995).

70. Robinson GN, Johnson TL, Hoffman MD. High performance polyurethane coating systems utilizing oxazolidine-based reactive diluents. *J Coat Technol* 66:69–74 (1994).
71. Adams RC. Use of isophthalic resins in high solids coatings. *Polym Paint Colour J* 186:17–20 (1996).
72. Rupa Vani JN, Lakeshmi VV, Sitaraman BS, Krishnamurti N. Synthesis of allyl phenyl acrylates and their evaluation as reactive diluents in UV-curable coatings. *Prog Org Coat* 21:339–352 (1993).
73. Kuo C, Zhao C, Nirali L, Sirlikov S. Low VOC alkyd coatings using (meth)acrylate reactive diluents. *Am Paint Coat J* 79:41–51 (1994).
74. Hoffman. A reactive diluent for flexible, high solids polyurethane coatings. *Am Paint Coat J* 80:46–51 (1995).
75. Dirlikov S, Islam MS, Frischinger I, Lepkowski T, Murturi P. Increasing high-solids with a weed. *Ind Finish* 68:17–20 (1992).
76. Banov A. Answers to VOC, HAP headaches: a linseed oil-based reactive diluent, solvent reformulation options. *Am Paint Coat J* 79:45–46 (1994).
77. Finzel W. Volatile methyl siloxanes as exempt solvents in protective coatings. *J Coat Technol* 68:69–72 (1996).
78. Kamath VR, Sargent JDJ. Production of high solids acrylic coating resins with *t*-amyl peroxides: a new way to meet VOC requirements. *Chem Eng World* 31:57–62 (1996).
79. Nakano S, Morimoto T. High-solids coatings using benzyllanilinium sulfonates-II, α , α -dimethylbenzylpyridinium *p*-toluenesulfonate, an effective blocked sulfonic acid. *J Coat Technol* 68:83–90 (1996).
80. Gould ML, Dettloff ML, Whiteside RC Jr. Linear pendant anhydrides: novel building blocks for high solids, high performance coatings. *Prog Org Coat* 29:117–126 (1996).
81. Wicks DA, Yeske PE. Imine-isocyanate chemistry: new technology for environmentally friendly, high solids coatings. In: *Developing Safer Chemicals: Green Chemistry for Pollution Prevention*, Vol 640 (Devito SC, Garrett RL, eds). Washington:American Chemical Society, 1996.
82. Bieleman JH. New additives improve performance of waterborne paints. *Am Paint Coat J* 80:30–34 (1996).
83. Karsa DR, Davies WD, eds. *Waterborne Coatings and Additives*. Cambridge: The Royal Society of Chemistry, 1995.
84. Provder T, Winnik MA, Urban MW, eds. *Film Formation in Waterborne Coatings*. Washington: American Chemical Society, 1996.
85. Padget JC. Polymers for water-based coatings: a systematic overview. *J Coat Technol* 66:89–105 (1994).
86. Water-reducible resins. In: *Surface Coatings: Raw Materials and Their Usage*, Vol 1. New York: Chapman and Hall, 1993:263–292.
87. Mirgel V. New resin systems for high performance waterborne coatings. *Prog Org Coat* 22:273–277 (1993).
88. Hergernrother R, Ruttman G. Polyurethane coatings meet VOC challenge. *J Prot Coat Linings* 7:40–46 (1990).
89. Brown W. Aromatic polycarbodiimides: a new class of crosslinkers for water-borne coatings. *Surf Coat Int* 78:238–242 (1995).
90. Eslinger DR. Aliphatic epoxy emulsion crosslinker for water-borne coatings. *J Coat Technol* 67:45–50 (1995).
91. Poggio T, Lenti D, Masini L. Water-borne fluoroelastomeric coatings with high barrier properties. *J Am Oil Colour Chem Assoc* 78:289–293 (1995).
92. Neimann J. Waterborne coatings for the automotive industry. *Prog Org Coat* 21:189–203 (1992).
93. Blank WJ. Novel polyurethane polyols for waterborne and high solids coatings. *Prog Org Coat* 20:235–259 (1992).
94. Clancy S. The paint revolution. *Transp Eng* 10:13–19 (1994).
95. Water-borne coating improves air quality. *Prod Finish* 60:59–61 (1996).
96. Cornwell DW. Developments on water-based and low VOC coatings for the protection of structural steel. *Surf Coat Int* 77:455–459 (1994).
97. Kobayashi T. Pigment dispersion in water-reducible paints. *Prog Org Coat* 28:79–87 (1996).
98. Klein RJ. Formulating low odor, low VOC interior paints. *Mod Paint Coat* 83:37–39 (1993).
99. Donohue MD, Geiger JL, Kaimos AA, Nielsen KA. Reduction of volatile organic compound emissions during spray painting. In: *Green Chemistry: Designing Chemistry for the Environment*, Vol 626 (Anastas PT, Williamson TC, eds). Washington: American Chemical Society, 1996:152–167.
100. White TF. An economic solution to meeting VOC regulations. *Met Finish* 89:55–58 (1991).
101. Nielsen KA, Glancy CW. *Precursor Coating Composition Suitable for Spraying with Supercritical Fluids as Diluents*. Danbury, CT: Union Carbide Chemicals and Plastics Technology Corporation, 1996.
102. Lee C, Hoy KL, Donohue MD. *Supercritical Fluids as Diluents in Liquid Spray Application of Coatings*. Danbury, CT: Union Carbide Chemicals and Plastics Company, 1990.
103. Marrion AR, ed. *The Chemistry and Physics of Coatings*. Cambridge: The Royal Society of Chemistry, 1994.
104. McGinniss VD. Advances in environmental benign coatings and adhesives. *Prog Org Coat* 27:153–161 (1996).
105. Jones FH. Toward solventless liquid coatings. *J Coat Technol* 68:25–36 (1996).
106. Caddick S. Microwave-assisted organic reactions. *Tetrahedron* 51:10403–10432 (1995).
107. Budavari S, O'Neil M, Smith A, Heckelman PE, eds. *The Merck Index*. Rahway: Merck and Co., 1989.
108. Femec DA, Mccaffrey RR. Solvent replacement in the synthesis of persubstituted phosphonitrilic hydroquinone prepolymer materials. *J Appl Polym Sci* 52:501–505 (1994).
109. Galvez N, Moreno-Manas M, Sebastian RM, Vallribera A. Dimethoxyethane as an alternative solvent for Schmidt reactions. Preparation of homochiral *N*-(5-Oxazolyl)oxazolidonones from *N*-acetoacetyl derivatives of oxazolidinones. *Tetrahedron* 52:1609–1616 (1996).
110. Ogawa A, Curran DP. Benzotrifluoride: a useful alternative solvent for organic reactions currently conducted in dichloromethane and related solvents. *J Org Chem* 62:450–451 (1997).
111. Molnar LK. *Polymer Based Solvents for Minimizing Pollution During the Synthesis of Fine Chemicals* [PhD. dissertation]. Cambridge, MA: Massachusetts Institute of Technology 1996. Also summarized in: Molnar LK, Buchwald SL, Hatton TA. Polymer based replacement solvents for minimizing pollution during the synthesis of fine chemicals. *Polym Mater Sci Eng* 75:113–114 (1996).
112. Seddon KR. Room-temperature ionic liquids: neoteric solvents for clean catalysis. *Kinet Catal* 37:693 (1996).
113. Seddon KR. Ionic liquids for clean technology. *J Chem Technol Biotechnol* 68:351–356 (1997).
114. Goldberg Y. *Phase Transfer Catalysis: Selected Problems and Applications*. Yverdon, Switzerland: Gordon and Breach Science Publishers, 1989.
115. Dehmlow EV, Dehmlow SS. *Phase Transfer Catalysis*. Weinheim: VCH, 1993.
116. Starks CM, Liota CL, Halpern M. *Phase-Transfer Catalysis: Fundamentals, Applications, and Industrial Perspectives*. New York: Chapman and Hall, 1994.
117. O'Donnell MJ. Asymmetric phase transfer reactions. In: *Catalytic Asymmetric Synthesis* (Ojima I, ed). New York: VCH, 1993:389–412.
118. Darrt CB, Davis ME. Catalysis for environmentally benign processing. *Ind Eng Chem Res* 33:2887–2899 (1994).
119. Lim PK, Zhong Y. Chemically benign synthesis at organic-water interface. In: *Green Chemistry: Designing Chemistry for the Environment* (Anastas PT, Williamson TC, eds). Washington: American Chemical Society, 1996:168–177.
120. Papadogianakis G, Sheldon RA. Catalytic conversions in water: environmentally attractive processes employing water soluble transition metal complexes. *N J Chem* 20:175–185 (1996).
121. Fendler JH, Fendler EJ. *Catalysis in Micellar and Macromolecular Systems*. New York: Academic Press, 1975.
122. Bunton CA. Kinetics and catalysis. In: *Microheterogeneous*

- Systems, Vol 38 (Gratzel M, Kalyanasundaram K, eds). New York:Marcel Dekker, 1991;13–28.
123. Monflier E, Bourdauducq P, Couturier JL, Kervennal J, Suisse I, Mortreux A. Solvent-free telomerization of butadiene with water into octadienols in the presence of nonionic surfactant: efficient micellar catalysis. *Catal Lett* 34:201–212 (1995).
 124. Rathman JF, Siswanto C, Battal T. Alkylation of phenol and anilin in aqueous surfactant solutions by micellar phase-transfer catalysis. *Abstr Amer Chem Soc* 211:120–COLL (1996).
 125. Kust PR, Rathman JF. Synthesis of surfactants by micellar autocatalysis: *N,N*-dimethyldodecylamine *N*-oxide. *Langmuir* 11:3007–3012 (1995).
 126. Li CJ. Aqueous Barbier-Grignard type reaction: scope, mechanism, and synthetic applications. *Tetrahedron* 52:5643–5668 (1996).
 127. Shu HY, Perlmutter HD, Shaw H. Application of a droplet column type two-phase reactor for the epoxidation of cyclooctene in water as an alternative solvent. *Ind Eng Chem Res* 34:3761–3765 (1995).
 128. Shaw H, Perlmutter HD, Chen G, Arco SD, Quibuyen TO. Free-radical bromination of selected organic compounds in water. *J Org Chem* 62:236–237 (1997).
 129. Tester JW, Holgate HR, Armellini FJ, Webley PA, Killilea WR, Hong GT, Barner HE. Supercritical water oxidation technology. In: *ACS Symposium Series*, Vol 518. Washington: American Chemical Society, 1993;35–75.
 130. Savage PE, Gopalan S, Mizan TI, Martino CJ. Reactions at supercritical conditions: applications and fundamentals. *AIChE J* 41:1723–1778 (1995).
 131. Aki SNVK, Ding ZY, Abraham MA. Catalytic supercritical water oxidation: stability of Cr_2O_3 catalyst. *AIChE J* 42:1995–2004 (1996).
 132. Clercq ML. Ceramic reactor for use with corrosive supercritical fluids. *AIChE J* 42:1798–1799 (1996).
 133. Black H. Supercritical carbon dioxide: the “greener” solvent. *Environ Sci Technol* 30:124A–128A (1996).
 134. Eckert CA, Knutson BL, Debenedetti PG. Supercritical fluids as solvents for chemical and materials processing. *Nature* 383:313–318 (1996).
 135. Romack TJ, Maury EE, Desimone JM. Precipitation polymerization of acrylic acid in supercritical carbon-dioxide. *Macromolecules* 28:912–915 (1995).
 136. Kapellen KK, Mistele CD, Desimone JM. Synthesis of poly(2,6-dimethylphenylene oxide) in carbon-dioxide. *Macromolecules* 29:495–496 (1996).
 137. Romack TJ, Kipp BE, Desimone JM. Polymerization of tetrafluoroethylene in a hybrid carbon dioxide aqueous-medium. *Macromolecules* 28:8432–8434 (1995).
 138. Clark MR, Desimone JM. Cationic polymerization of vinyl and cyclic ethers in supercritical and liquid carbon-dioxide. *Macromolecules* 28:3002–3004 (1995).
 139. Canelas DA, Betts DE, DeSimone JM. Dispersion polymerization of styrene in supercritical carbon-dioxide—importance of effective surfactants. *Macromolecules* 29:2818–2821 (1996).
 140. McClain JB, Betts DE, Canelas DA, Samulski ET, Desimone JM, Londono JD, Cochran HD, Wignall GD, Chilluramartino D, Triolo R. Design of nonionic surfactants for supercritical carbon-dioxide. *Science* 274:2049–2052 (1996).
 141. Xiao JL, Nefkens SCA, Jessop PG, Ikariya T, Noyori R. Asymmetric hydrogenation of α,β -unsaturated carboxylic acids in supercritical carbon-dioxide. *Tetrahedron Lett* 37:2813–2816 (1996).
 142. Jessop PG, Hsiao Y, Ikariya T, Noyori R. Homogeneous catalysis in supercritical fluids: hydrogenation of supercritical carbon-dioxide to formic acid, alkyl formates, and formamides. *J Am Chem Soc* 118:344–355 (1996).
 143. Burk MJ, Feng SG, Gross MF, Tumas W. Asymmetric catalytic-hydrogenation reactions in supercritical carbon-dioxide. *J Am Chem Soc* 117:8277–8278 (1995).
 144. Molero Gomez A, Pereyra Lopez E, Martinez de la Ossa E. Recovery of grape seed oil by liquid supercritical carbon dioxide extraction: a comparison with convention solvent extraction. *Chem Eng J* 61:227–231 (1996).
 145. Krukons V, Brunner G, Perrut M. Industrial operations with supercritical fluids: current processes and perspectives on the future. In: *3rd International Symposium of Supercritical Fluids*, 17–19 October 1994, Strasbourg, France. Vandoeuvres-Nancy (Meurthe-et-Moselle): INPL, 1994.
 146. Dolezal IS, Segebarth KP, Zennegg M, Wunderli S. Comparison between supercritical fluid extraction (SFE) using carbon dioxide/acetone and conventional Soxhlet extraction with toluene for the subsequent determination of PCDD/PCDF in a single electrofilter ash sample. *Chemosphere* 31:4013–4024 (1995).
 147. Clement RE, Koester CJ, Eiceman GA. Environmental analysis. *Anal Chem* 65:85R–116R (1993).
 148. Alzaga R, Bayona JM, Barcelo D. Use of supercritical fluid extraction for pirimicarb determination in soil. *J Agric Food Chem* 43:398–399 (1995).
 149. Reighard TS, Olesik SV. Comparison of the extraction of phenolic and nitroaromatic pollutants using supercritical and enhanced-fluidity liquid methanol- CO_2 mixtures. *J Chromatogr A* 737:233–242 (1996).
 150. Roth M. Thermodynamic prospects of alternative refrigerants as solvents for supercritical fluid extraction. *Anal Chem* 68:4474–4480 (1996).
 151. Christian SD, Scamehorn JF. Use of micellar-enhanced ultrafiltration to remove dissolved organics from aqueous streams. In: *Surfactant-based Separation Processes*, Vol 33 (Scamehorn JF, Jeffrey HH, eds). New York:Marcel Dekker, 1989;3–28.
 152. Hurter PN, Hatton TA. Solubilization and extraction of polycyclic aromatic hydrocarbons in polyethylene oxide-polypropylene oxide block copolymer micelles. *Langmuir* 8:1291–1299 (1992).
 153. Nagarajan R, Barry M, Ruckenstein E. Unusual selectivity in solubilization by block copolymer micelles. *Langmuir* 2:210–215 (1986).
 154. Hurter PN, Anger LA, Vojvodich LJ, Keuey CA, Cohen RE, Hatton TA. Amphiphilic polymer solutions as novel extractants for environmental applications. In: *Solvent Extraction in the Process Industries—Proceedings of International Solvent Extraction Conference '93*, Vol 3 (Logsdail DH, Slater MJ, eds). London:Elsevier, 1993;1663–1670.
 155. Lebens PJM, Keurentjes JTF. Temperature-induced solubilization of hydrocarbons in aqueous block copolymer cosolution. *Ind Chem Res* 35:3415–3421 (1996).
 156. Walter H, Brooks DE, Fisher D. Partitioning in Aqueous Two-Phase Systems. Theory, Methods, Uses and Applications to Biotechnology. Orlando, FL:Academic Press, 1985.
 157. Rogers RD, Zhang J. New technologies for metal ion separations: polyethylene glycol based-aqueous biphasic systems and aqueous biphasic extraction chromatography. In: *Ion Exchange and Solvent Extraction*, Vol 13 (Marcus Y, Marinsky JA, eds). New York:Marcel Dekker, 1997.
 158. Rogers RD, Bond AH, Bauer CB, Griffin ST, Zhang J. Polyethylene glycol-based aqueous biphasic systems for extraction and recovery of dyes and metal/dye complexes. In: *Value Adding through Solvent Extraction—Proceedings of the International Solvent Extraction Conference '96*, Vol 2 (Shallcross DC, Paiman R, Pavcic LM, eds). Victoria, Australia:The University of Melbourne, 1996;1537–1542.
 159. Kaminski M, Landsberger S, Nunez L, G.F. Vandegrift. Sorption capacity of ferromagnetic microparticles coated with CMPO. *Sep Sci Technol* 32:115–126 (1997).
 160. Nunez L, Buchholz BA, Kminski M, Aase SB, Brown NR, Vandegrift GF. Actinide separation of high-level waste using solvent extractants on magnetic microparticles. *Sep Sci Technol* 31:1393–1407 (1996).
 161. Joback KG. Solvent substitution for pollution prevention. In: *Pollution Prevention via Process and Product Modifications*, Vol 90 (El-Hawagi MM, Petrides DP, eds). New York:American Institute of Chemical Engineers, 1994;98–104.
 162. Fredenslund A, Jones RL, Prausnitz JM. Group contribution

- estimation of activity coefficients in nonideal liquid mixtures. *AIChE J* 21:1086–1099 (1975).
163. Gani R, Brignole EA. Molecular design of solvents for liquid extraction based on UNIFAC. *Fluid Phase Equilib* 13:331–340 (1983).
 164. Brignole EA, Bottini S, Gani R. A strategy for the design and selection of solvents for separation processes. *Fluid Phase Equilib* 29:125–139 (1986).
 165. Gani R, Nielsen B, Fredenslund A. A group contribution approach to computer-aided molecular design. *AIChE J* 37 (1991).
 166. Gani R, Fredenslund A. Computer-aided molecular and mixture design with specified property constraints. *Fluid Phase Equilib* 82:39–46 (1993).
 167. Naser SF, Founier RL. A system for the design of an optimum liquid-liquid extractant molecule. *Comput Chem Eng* 15:397–414 (1991).
 168. Macchietto S, Odele O, Omatsone O. Design of optimal solvents for liquid-liquid extraction and gas absorption processes. *Trans I Chem E* 68:429–433 (1990).
 169. Odele O, Macchietto S. Computer-aided design: a novel method for optimal solvent selection. *Fluid Phase Equilib* 82:47–54 (1993).
 170. Pretel EJ, Lopez PA, Bottini SB, Brignole EA. Computer-aided molecular design of solvents for separation processes. *AIChE J* 40:1349–1360 (1994).
 171. Klein JA, Wu DT, Gani R. Computer-aided mixture design with specified property constraints. *Comput Chem Eng* 16:s229–s236 (1992).
 172. Duvedi AP, Achenie LEK. Designing environmentally safe refrigerants using mathematical programming. *Chem Eng Sci* 51:3727–3739 (1996).
 173. Venkatasubramanian V, Chan K, Caruthers JM. Evolutionary design of molecules with desired properties using the genetic algorithm. *J Chem Inf Comput Sci* 35:188–195 (1995).
 174. Meniai AH, Newsham DMT. A computer-aided molecular design of solvents for liquid-liquid extraction. *Trans I Chem E* 74:695–702 (1996).
 175. Meniai AH, Newsham DMT. The selection of solvents for liquid-liquid extraction. *Trans I Chem E* 74:78–87 (1996).
 176. Rouvray DH. Predicting chemistry from topology. *Sci Am* 255:40–47 (1986).
 177. Ivanciuc O. CODESSA version 2.13 for Windows. *J Chem Inf Comput Sci* 37:405–406 (1997).
 178. Yalkowsky SH, Banerjee S. *Aqueous Solubility. Methods of Estimation for Organic Compounds*. New York:Marcel Dekker, 1992.
 179. Kan AT, Tomson MB. UNIFAC prediction of aqueous and nonaqueous solubilities of chemicals with environmental interest. *Environ Sci Technol* 30:1369–1376 (1996).
 180. Kier LB, Hall LH. *Molecular Connectivity in Chemistry and Drug Research*. New York:Academic Press, 1976.
 181. Kier LB, Hall LH. *Molecular Connectivity in Structure-Activity Analysis*. New York:Wiley, 1986.
 182. Katritzky AR, Lobanov VS, Karelson M. QSPR: the correlation and quantitative prediction of chemical and physical properties from structure. *Chem Soc Rev* 24:279–287 (1995).
 183. Nirmalakhandan NN, Speece RE. Prediction of aqueous solubility of organic chemicals based on molecular structure. *Environ Sci Technol* 22:328–338 (1988).
 184. Bodor N, Huang MJ. A new method for the estimation of the aqueous solubility of organic compounds. *J Pharm Sci* 81:954–960 (1992).
 185. Nelson TM, Jurs PC. Prediction of aqueous solubility of organic compounds. *J Chem Inf Comput Sci* 34:601–609 (1994).
 186. Sutter JM, Jurs PC. Prediction of aqueous solubility for a diverse set of heteroatom-containing organic compounds using a quantitative structure-property relationship. *J Chem Inf Comput Sci* 36:100–107 (1996).
 187. Carlson EC. Don't gamble with physical properties for simulations. *Chem Eng Prog* 92:35–46 (1996).
 188. DeVito SC. General principles for the design of safer chemicals: toxicological considerations for chemists. In: *Designing Safer Chemicals: Green Chemistry for Pollution Prevention*, Vol 640 (DeVito SC, Garrett RL, eds). Washington:American Chemical Society, 1996;16–59.
 189. Lai DY, Woo Y, Argus MF, Arcos JC. Cancer risk reduction through mechanism based molecular design of chemicals. In: *Designing Safer Chemicals: Green Chemistry for Pollution Prevention*, Vol 640 (DeVito SC, Garrett RL, eds). Washington:American Chemical Society, 1996;62–73.
 190. Milne GWA, Wang S, Fung V. Use of computers in toxicology and chemical design. In: *Designing Safer Chemicals: Green Chemistry for Pollution Prevention*, Vol 640 (DeVito SC, Garrett RL, eds). Washington:American Chemical Society, 1996;138–155.
 191. Sanderson DM, Earnshaw CG. Computer prediction of possible toxic reaction from chemical structure: the DEREK system. *Hum Exp Toxicol* 10:261–273 (1991).
 192. Ridings JE, Barratt MD, Cary R, Earnshaw CG, Eggington CE, Ellis MK, Judson PN, Langowski JJ, Marchant CA, Payne MP, Watson WP, Yih TD. Computer prediction of possible toxic action from chemical structure: an update on the DEREK system. *Toxicology* 106:267–279 (1996).
 193. Bristol DW, Wachsmann JT, Greenwell A. The NIEHS Predictive-Toxicology Evaluation Project. *Environ Health Perspect* 104(Suppl 5):1001–1010 (1996).
 194. Reichardt C. *Solvents and Solvent Effects in Organic Chemistry*. New York:VCH, 1990.
 195. Crabtree EW, El-Halwagi MM. Synthesis of environmentally acceptable reactions. In: *Pollution Prevention via Process and Product Modifications*, Vol 90 (El-Halwagi MM, Petrides DP, eds). New York:American Institute of Chemical Engineers, 1994;117–127.
 196. Stefanis SK, Buxton A, Livingston AG, Pistikopoulos EN. A methodology for environmental impact minimization: solvent design and reaction path issues. *Comput Chem Eng* 20:S1419–S1424 (1996).
 197. Modi A, Aumond JP, Mavrouniotis M, Stephanopoulos G. Rapid plant wide screening of solvents for batch processes. *Computers Chem Eng* 20(Suppl):S375–S380 (1996).
 198. Aumond JP. Personal communication.
 199. Varerkar MP. Formulating high solids coatings: the solution to the VOC problem. *Paint India* 45:19–30 (1996).
 200. Gendron GR. Information exchange: techniques and their effects on pollution prevention innovation in the United States Air Force [Master's thesis]. Fort Collins CO:National Technology University, 1994.
 201. Kirschner EM. Environment, health concerns force shift in use of organic solvents. *Chem Eng Prog* 72:13–20 (1994).